CANADIAN THESES ON MICROFICHE

I.S.B.N.

THESES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL-339 (r. 82/08)

Canada

National Library of Canada
Canadian Theses Division
Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Division des thèses canadiennes

0-315-06126-7

54056

PERMISSION TO MICROFILM — AUTORISATION DE MICROFILMER

- Please print or type — Écrire en lettres moulées ou dactylographier

Full Name of Author — Nom complet de l'auteur
JOHN GYLBERT TIMMERMANS

Date of Birth — Date de naissance 1952 - 06 - 02	Country of Birth — Lieu de naissance HOLLAND

Permanent Address — Résidence fixe
483 - MIDRIDGE DRIVE SE.
CALGARY, ALBERTA
T2X - 1B2

Title of Thesis — Titre de la thèse
FALL VERSUS SPRING APPLICATION OF NITROGEN FERTILIZERS ON DRYLAND AND IRRIGATED SOILS OF SOUTHERN ALBERTA

University — Université
UNIVERSITY OF ALBERTA

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée
MASTER OF SCIENCE IN SOIL SCIENCE

Year this degree conferred — Année d'obtention de ce grade 1981	Name of Supervisor — Nom du directeur de thèse DR. J. A. ROBERTSON

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur.

Date October 16, 1981	Signature J G Timmermans

NL-91 (4/77)

THE UNIVERSITY OF ALBERTA

FALL VERSUS SPRING APPLICATION OF NITROGEN FERTILIZERS ON DRYLAND AND IRRIGATED SOILS OF SOUTHERN ALBERTA

by

© JOHN GYLBERT TIMMERMANS

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

SOIL SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA
FALL, 1981

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR JOHN GYLBERT TIMMERMANS

TITLE OF THESIS FALL VERSUS SPRING APPLICATION OF NITROGEN FERTILIZERS ON DRYLAND AND IRRIGATED SOILS OF SOUTHERN ALBERTA

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED FALL, 1981

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(Signed) John G. Timmermans

PERMANENT ADDRESS:

483 Midridge Drive S.E.
Calgary, Alberta, T2X 1B2

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Fall Versus Spring Application of Nitrogen Fertilizers on Dryland and Irrigated Soils of Southern Alberta" submitted by John Gylbert Timmermans in partial fulfillment of the requirements for the degree of Master of Science in Soil Science.

J. A. Robertson
Supervisor

Marvin Nyborg

Saul Zalik

Date 1981-10-16

This Thesis is dedicated to my wife, Wendy.
Without her patience, encouragement, friendship and love,
this project would never have been completed.

ABSTRACT

This study was initiated to investigate the occurrence and extent of over-winter changes in the level of soil and fertilizer mineral N in irrigated and dryland soils of the Brown, Dark Brown and Black soil zones of southern Alberta. Over winter sampling of soils at four plot sites in the first year of the study revealed changes in the levels of NH_4-N and NO_3-N in an irrigated stubble plot, dryland stubble and fallow plots, and an irrigated stubble plot with varying levels of residual fertilizer N. Levels of mineral N decreased from January to May, and the extent of these reductions was related soil moisture over winter, and level of mineral N in January.

Comparisons of fall with spring fertilizer treatments in the second year of the study, including variables of N-source, placement methods, the use of a nitrification inhibitor and soil moisture in fall were made at six plot sites to include irrigated and dryland plots in the three soil zones. In terms of barley yield, N uptake by the crop, and recovery of mineral N from fall applied treatments, there was no evidence of over-winter losses of fall-applied N, or that fall applied N resulted in lower yields than spring applied N.

^{15}N-labelled NH_4-N and NO_3-N were added to six soil samples, representing the topsoil and "subsoil" of two southern Alberta soils and one central Alberta soil. The soils were incubated for 90 days at both -1 and +4°C, and at field capacity moisture content. Recovery of applied NO_3-N was complete by KCl extraction, but not by the modified Kjeldahl procedure to include NO_2^- and NO_3-N. Recovery of added NO_3-N was complete regardless of soil or incubation temperature, indicating that, as might be expected, that no denitrification occurred, and that no immobilization occurred. Nitrification occurred, at -1°C, but more extensively at +4°C. The extent of nitrification of added N was influenced by soil, depth and incubation temperature.

ACKNOWLEDGEMENTS

Sincere appreciation is extended to Dr. J. A. Robertson, Professor, Department of Soil Science, for his encouragement and committment, and for serving as my supervisor throughout the course of this work.

Special thanks are also extended to Dr. J. B. Bole, Soil Scientist, Canada Agriculture Research Station, Lethbridge, for his guidance and participation in the laboratory and field work at the Research Station.

Grateful acknowledgement is extended to Dr. M. Nyborg, Professor, and Dr. W. B. McGill, Head, Department of Soil Science, for their suggestions during the planning of this work, for their assistance in its completion, and for serving on the thesis committee; and to Dr. S. Zalik, Professor, Department of Plant Science, for also serving on the committee.

The arrangements made by Dr. D. C. MacKay, Head, Soils Section, Canada Agriculture Research Station, Lethbridge, which allowed me to work at the excellent facility there are gratefully acknowledged.

Contributions toward the completion of this thesis from the following are sincerely appreciated:

Mr. Richard Leitch, Soils Specialist, formerly at the Agricultural Soil and Feed Testing Laboratory, Edmonton, for his help in the analysis of the soil samples.

My friend Mr. John Unrau, for his good humor and help with all aspects of the work in Lethbridge.

ACKNOWLEDGEMENTS (continued)

Mrs. Mary-Ellen Funnell, Mr. Floyd Anderson, Mr. Walter Hulstein, Mrs. Alice Bligh, Mrs. Millie Baird and Mr. Robert Follis for their help with laboratory analyses.

Mr. Alf Lagler and Mrs. Echo Coulter for their help in the computer room.

Mr. Mel Kiemele and Mr. Ted Kaminski for their help in the field.

Mr. Nobby Nakahama for drafting the figures in the text.

Mrs. Donna McKenzie for typing the manuscript.

Financial support from the Alberta Agricultural Research Trust and from the Pool/Co-op Agronomy Committee is gratefully acknowledged.

TABLE OF CONTENTS

CHAPTER PAGE

1. INTRODUCTION 1
2. LITERATURE REVIEW 4
    - 2.1 Mineralization 4
    - 2.2 Nitrification 6
    - 2.3 Denitrification 9
    - 2.4 Leaching Losses of Nitrogen 14
    - 2.5 Effect of Method of Placement on Nitrification 16
    - 2.6 Nitrification Inhibitors 17
    - 2.7 Fall versus Spring Application of Nitrogen Fertilizers 19
    - 2.8 Summary of Literature Review 22
3. MATERIALS AND METHODS 25
    - 3.1 Preliminary Field Experiments 1975-76 24
    - 3.2 Main Field Experiments 1976-77 24
    - 3.3 Analytical Procedures 25
    - 3.4 N-15 Incubation Study 27
        - 3.4.1 Experimental Design 28
        - 3.4.2 Analytical Methods 28
4. RESULTS 33
    - 4.1 Preliminary Field Experiments 33
        - 4.1.1 Over-winter changes in the level of soil mineral N in a stubble soil at Lethbridge 33

TABLE OF CONTENTS (continued)

CHAPTER PAGE

4.1.2 Over-winter changes in the level of soil mineral N in a fallowed soil at Lethbridge 35

4.1.3 Over-winter changes in the level of mineral N in a stubble soil at Vauxhall 39

4.2 Main Field Experiments 42

4.2.1 Effect of fall vs spring broadcast-applied N on yield of barley and N uptake 43

4.2.2 Effect of N-source on yield of barley, N uptake, and level of mineral N recovered in spring 47

4.2.3 Effect of band-placement of fall-applied urea, with and without the nitrification inhibitor ATC 57

4.2.4 Effect of fall irrigation and fall-applied $Ca(NO_3)_2$ on yield of barley, N uptake and recovery of fertilizer N in spring 64

4.3 Recovery and Transformation of N-15-Labelled Fertilizers in a Soil Incubation Experiment 74

4.3.1 Percent recovery of applied N by Kjeldahl analysis, and by KCl extraction and distillation using direct measurement and indirect (subtraction) techniques 75

4.3.2 Effect of incubation temperature, soil and depth on nitrification . . . 80

5. DISCUSSION OF RESULTS 82

6. CONCLUSIONS 91

7. REFERENCES 92

8. APPENDICES 102

LIST OF TABLES

TABLE PAGE

1. Mineral (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in preliminary stubble plots at Lethbridge 35

2. Mineral N (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in a preliminary summerfallow plot at Lethbridge 37

3. Mineral (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in a preliminary stubble plot at Vauxhall 40

4. Yield of barley grain (t/ha) with fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$ 44

5. Nitrogen content of barley grain (kg/ha) from fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$ 46

6. Nitrogen uptake (kg/ha) by grain plus straw from fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$ 47

7. The effect of fall and spring broadcast-applied N sources on yield of barley grain (t/ha) at dryland and irrigated sites 49

8. The effect of fall and spring broadcast-applied N sources on N content of barley-grain (kg/ha) at dryland and irrigated sites 50

9. The effect of fall and spring broadcast-applied N sources on N uptake by barley grain plus straw (kg/ha) at dryland and irrigated sites 51

10. Average effect of fall and spring applied N-source on N uptake by grain plus straw (kg/ha) . . 53

11a. Levels of mineral N (kg/ha) recovered in spring, 1977 after fall broadcast-application of N sources at dryland sites 54

11b. Levels of mineral N (kg/ha) recovered in spring, 1977 after fall broadcast-application of N sources at irrigated sites 55

LIST OF TABLES (continued)

TABLE PAGE

12. Yield of barley grain (t/ha) with fall application of urea by broadcasting and band-placement with and without the nitrification inhibitor ATC 59

13. Nitrogen uptake by grain (kg/ha) with fall application of urea by broadcasting and band-placement with and without the nitrification inhibitor ATC 60

14. Nitrogen uptake by grain plus straw (kg/ha) with fall application of urea by broadcasting and band-placement with and without the nitrification inhibitor ATC 61

15a. Recovery of NH_4-N, NO_3-N and (NH_4+NO_3)-N (kg/ha) at dryland sites in spring, from urea fall-applied by broadcasting, and banding with and without the nitrification inhibitor ATC . . . 62

15b. Recovery of NH_4-N, NO_3-N and (NH_4+NO_3)-N (kg/ha) at irrigated sites in spring, from urea fall-applied by broadcasting, and banding with and without the nitrification inhibitor ATC . . . 63

16. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on yield of barley (t/ha) at dryland and irrigated sites 67

17. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on N content of barley grain (kg/ha) at dryland and irrigated sites . . . 68

18. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on N uptake by grain plus straw (kg/ha) at dryland and irrigated sites . . . 69

19a. Recovery of (NH_4+NO_3)-N and fertilizer N (kg/ha) to a depth of 30 cm in spring, from fall-irrigated, and fall broadcast-applied $Ca(NO_3)_2$ treatments at dryland sites 71

19b. Recovery of (NH_4+NO_3)-N and fertilizer N (kg/ha) to a depth of 30 cm in spring, from fall-irrigated, and fall broadcast-applied $Ca(NO_3)_2$ treatments at irrigated sites 72

LIST OF TABLES (continued)

PAGE

20. Average recovery of fertilizer NO_3-N (kg/ha) in spring, from fall-applied $Ca(NO_3)_2$ on fall irrigated and non-irrigated treatments at dryland and irrigated sites 74

21. Percent of applied N recovered by Kjeldahl digestion by steam distillation and ^{15}N technique, and by steam distillation and the subtraction method 77

22. Percent recovery of applied NO_3-N at zero-time, and after incubation for 90 days at -1° and +4°C at field capacity 79

23. Percent recovery of applied $^{15}NH_4$-N as $^{15}NO_3$-N, measured by KCl extracted ^{15}N 81

LIST OF FIGURES

FIGURE PAGE

1 Over-winter changes in the level of soil mineral N to a depth of 60 cm in preliminary Lethbridge stubble plots 36

2 Over-winter changes in the level of soil mineral N to a depth of 60 cm at a Lethbridge preliminary fallow plot 38

3 Over-winter changes in the level of soil mineral N to a depth of 60 cm in a preliminary Vauxhall stubble plot 41

1. INTRODUCTION

Fall application of nitrogen (N) fertilizers for the production of spring-sown crops has become an increasingly popular practice in the Prairie Provinces during the past decade. This practice benefits the fertilizer industry as it permits more efficient use of production, marketing, and distribution facilities. Advantages to the farmer include lower prices and a greater certainty of supply of fertilizers in fall than in spring. Soil conditions, availability of time, equipment, and labor often favor fall-application.

Prior to work done in the 1970's in the Prairie Provinces, it was generally accepted that N fertilizers were as effective when applied in fall as in spring. Since then however, some studies conducted in Alberta, Saskatchewan and Manitoba have shown that fall-applied N often produces lower yields than spring-applied N.

The ammonium ion (NH_4^+) is strongly held by the cation exchange complex of clay and organic matter. It is therefore not readily subject to loss by leaching. Unlike NH_4^+, the nitrate ion (NO_3^-) is subject to loss through leaching, runoff, and biological and chemical denitrification. Nitrogen loss by denitrification can therefore only occur after nitrification.

Most prairie crops absorb the major portion of their N requirement as nitrate-nitrogen (NO_3-N). When conditions in fall, winter and early spring allow microbial growth, substantial nitrification can occur. This results in formation and accumulation of NO_3-N, if ammonium-nitrogen (NH_4-N) is available. Variable amounts of denitrification can occur between the time of application, and the time of crop demand in spring and summer, resulting in N losses and reduced crop yields due to fall rather than spring application. Successes have been achieved in attempts to slow the rate of nitrification by band-placement and by the use of chemical nitrification inhibitors. In some areas where losses were shown to occur however, these management practices did not prove to be as effective as spring application of N fertilizers.

Changes in fertilizer manufacturing technology and a recent general awareness of the potential N losses resulting from fall application have led to an increased production and use of ammoniacal fertilizers, especially urea and anhydrous ammonia. Since the practice of fall application continues to increase, further research is needed to investigate the potential for losses over winter and the relative effectiveness of techniques to minimize these losses.

To the knowledge of the author, few comparisons of fall to spring application of nitrogenous fertilizers on the Brown, Dark Brown and Black soil zones of southern Alberta have been published. Therefore, the present study was initiated with the following objectives:

1. To determine if over-winter losses of fertilizer nitrogen occur.

2. To determine if fall-applied N fertilizers result in lower N uptake and yields than spring-applied N fertilizers.

3. To compare the performance of various N fertilizers on soils of the Brown, Dark Brown and Black soil zones of southern Alberta.

4. To compare nitrogen distribution and over-winter transformations in dryland soils to those which have been irrigated for a number of years.

5. To study the fate of fall-applied NO_3-N under conditions of varying soil moisture.

6. To observe N transformations under simulated winter and early spring conditions by using N-15 labelled NH_4 and NO_3-N in laboratory incubated soils.

2. LITERATURE REVIEW

Inorganic N normally comprises a small portion of the total N in Ap horizons of mineral soils, yet uptake by plants and losses of N from the soil occur from the inorganic fraction. Organic soil N cannot be overlooked in any investigation of N fertility, but since the objective of the present study was to explore losses of N, this review will consider processes and conditions that affect N transformations. Management practices which are pertinent to the problems will also be discussed.

2.1 Mineralization

The decomposition of soil organic materials and subsequent release of NH_4-N is carried out primarily by heterotrophic soil microflora. The rate of mineralization can therefore be correlated with soil environmental factors affecting microbial growth. These include supply and nature of organic substrate, temperature, moisture, reaction and aeration status. Numerous articles in the literature on these aspects have been reviewed by Alexander (1961) and Clark (1967). This review will concentrate mainly on some of the more recent results reported in the literature.

The priming effect, or the stimulating effect of the addition of N fertilizers on the mineralization of soil organic matter has been reviewed by Broadbent (1965). Several possible reasons for this effect have been suggested. When roots of growing plants stimulated by N fertilizers are present, activity of the rhyzosphere population will increase in relation to available N. Mineralization of soil organic N could occur proportionally to this increased activity. Another explanation of the enhancement of soil N uptake following addition of fertilizer N proposes that root growth stimulated by fertilizer N increases the volume of soil utilized by the plant, thereby increasing uptake of soil N. These explanations fail however, to explain larger increases in the rate of soil N uptake brought about by the addition of NH_4-N rather than NO_3-N, and also the fact that mineralization has been shown to be stimulated under fallow conditions in the absence of growing plants. Broadbent (1965) suggested that osmotic effects of various fertilizer salts may have an effect on cell breakdown, resulting in increased mineralization of soil N. Parnas (1976) explained the priming effect as breakdown of soil organic matter enhanced by an increase in the average growth rate of heterotrophic bacteria. The addition of either carbon (C) or N when the ratio of these two substrates limits bacterial growth potential can increase or decrease organic matter breakdown. This change is dependent on whether the C:N ratio is moved closer to or away from the optimum for maximum bacterial growth.

The idea that certain chemical reactions are involved in splitting NH_4-N from organic and inorganic complexes is supported by Agarwal et al. (1971). The NH_4^+ ions are subsequently exchanged with cations in the surrounding soil solution. Although sulphate salts at low concentrations increased CO_2 evolution from incubated soil, chloride salts were better at increasing the rate of NH_4-N release. The different effects of anions is supported by results which showed different effects of two salts containing the same cation, but different anions. Broadbent and Nakashima (1971) used N-15 labelled NH_4Cl and $(NH_4)_2SO_4$ to study to their effect on mineralization rate, and also reported anionic effects. They also found that NH_4 salts increased the rate of NH_4-N release more than any other cation. They concluded that osmotic effects and the nature of both the soil and the fertilizer salt influence the rate of increase in mineralization.

Laura (1976) studied the effect of alkali salts and fresh organic residues on mineralization and CO_2 evolution. Although nitrification was stopped completely between exchangeable sodium percentage 70 and 92, mineralization increased dramatically. This increase may have been due in part to chemical decomposition rather than biological.

2.2 Nitrification

The two-step oxidation of NH_4^+ to NO_3^- is carried out by a much smaller segment of the total soil population than mineralization. Nitrosomonas and Nitrobacter, which are largely responsible for nitrification, are strictly aerobic chemoautotrophs. The nitrifying bacteria, performing more specific functions in the cycling of soil nitrogen than the mineralizing population, also have more specific environmental requirements for growth and activity. Factors affecting their growth include aeration status, temperature, pH, moisture and substrate supply. The literature reveals an abundance of works on this topic, and has been reviewed by Alexander (1965) and Campbell and Lees (1967). This review will consider some aspects of nitrification which have been recently reported and are more specifically applicable to the present study.

McLaren (1971) described the rate of nitrification as proportional to the growth of nitrifiers if the population is small in relation to its potential size, and if concentration of substrate is large enough to permit maximum specific growth rates.

The optimum temperature for nitrification has been the subject of many experiments. It has been reported as 30°to 32°C (Fisher and Parks 1958; Anderson and Boswell 1964) and as 25° to 27°C (Waksman and Madhok 1937; Justice and Smith 1962; Thiagalingam and Kanehiro 1973; Kowalenko and Cameron 1976). Some workers concluded that variations in temperature optima over which nitrification occurs is due to the initial population of nitrifiers (Anderson and Purvis 1955; Frederick 1957; Sabey et al. 1959; and Pang et al. 1975a). Nitrification occurs at a faster rate under moderately fluctuating temperature conditions, than at a constant mean (Campbell and Biederbeck 1972; Myers 1975). It has also been reported to occur at lower temperatures than previously thought. Nitrification at significant rates has been observed at temperatures approaching 0°C (Frederick 1956; Anderson 1960; Justice and Smith 1962; and Anderson and

and Boswell 1964; Malhi, 1978).

The variable results suggest optimum temperature for nitrification could be due in part to acclimatization of the nitrifying population. Myers (1975) found the optimum temperature for nitrification in a tropical soil to be 35°C. Mahendrappa et al. (1966) report that northern soils nitrified faster at 20° to 25°C than did southern soils, which nitrified faster at 30° to 35°C. Nitrite accumulation also differed in the same manner. Soils from a warmer climate accumulated nitrite at a lower temperature, while the northern soils did not, and vice-versa. With the use of sterile synthetic soils, Anderson et al.(1971) found that inoculated microflora from different soils nitrified at different rates. Inoculum from soils which were commonly frozen and thawed during winter resulted in more rapid nitrification at lower temperatures than inoculum from soils of warmer areas.

The effect of soil moisture on nitrification has also been reported by many workers. The nitrifying population responds readily to alterations in the soil moisture status. Early workers suggested the optimum soil moisture range of 50-60% of soil moisture holding capacity (Greaves and Carter 1920; Panganiban 1925; Russel et al. 1925). Justice and Smith (1962) and Miller and Johnson (1964) reported maximum rates of nitrification at soil moisture tensions of 0.3 bar and 0.5 bar, respectively. Although nitrification declines rapidly above optimum moisture levels, significant rates have been observed at 0 bar moisture tension (Dubey 1968).

The decline in the rate of nitrification as soil moisture decreases from the optimum level is more gradual. For example, a loamy sand at 15 bar moisture tension nitrified 73% of 100 ug N/g added as NH_4-N within two weeks under incubation at 25°C (Dubey 1968). Justice and Smith (1962) observed nitrification of 33% of 150 ug/g of NH_4-N in a soil at permanent wilting point incubated at 25°C for four weeks. Nitrification takes place in the film of water held at the surface of soil colloids (Lees and Quastel 1946; Meiklejohn 1953). It is conceivable that small films of water held against a tension of even more than 15 bar could provide microsites for nitrification to occur (Cook 1977)[1].

2.3 Denitrification

The term denitrification refers to the reduction of nitrite-nitrogen (NO_2-N), and NO_3-N to gaseous compounds such as nitric oxide (NO), nitrous oxide (NO_2) and molecular N (N_2), resulting in the loss of the nutrient from the soil. In the present study, denitrification will refer to the biological reduction. Chemical reduction resulting in loss can also occur, and is referred to as chemo-denitrification.

Biological denitrification is carried out by facultatively anaerobic heterotrophic bacteria capable of using NO_3^- or NO_2^- as a terminal electron acceptor in place of oxygen (Alexander 1977). As with other biological processes, the rate of denitrification is dependent on soil factors such as substrate supply, moisture, temperature, pH and nature and supply of organic carbon. In order for denitrification to occur, aeration must be restricted (Broadbent and Clark 1965).

---

[1] Cook, F.D. 1977. Personal communication. Professor, Department of Soil Science, University of Alberta, Edmonton, Alberta.

Workers have been aware of the process of denitrification since the late nineteenth century (Gayon and Dupetit 1886), but because of the difficulty associated with differentiation of this process from assimilatory nitrate reduction, the kinetics of this process are difficult to demonstrate. Assimilatory reduction of NO_3-N for the purpose of microbial protein synthesis results in disappearance of NO_3-N which is easily mistakenly interpreted as denitrification, especially in field experiments (Allison 1955).

Denitrification rates have been thought to be independant of NO_3^- concentration from 40 to approximately 500 ug/g (Broadbent 1951; Wijler and Delwiche 1954; and Cooper and Smith 1963). Bowman and Focht (1974) reported however, that denitrification rates are NO_3-N dependent at lower concentrations. This dependence gradually decreases at higher concentrations (1000 ug NO_3-N/ml). They observed a maximum rate of 150 ug N/ml/day from a soil suspension.

Soil moisture content is an important factor governing denitrification. In order for this process to occur, soil aeration must be restricted. High soil moisture levels reduce the volume of air-filled pores and the rate of movement of oxygen into and through the soil (Jansson and Clark 1952; Wijler and Delwiche 1954; Bremner and Shaw 1958; Allison et al. 1960; Broadbent and Clark 1965; Alexander 1977). Even in apparently well-aerated soils, anaerobic conditions may exist in the centers of soil aggregates or crumbs (Broadbent and Clark 1965; Alexander 1977). Anaerobic conditions favoring denitrification could therefore exist in much drier soils than was previously thought. Malhi (1978) observed measurable rates of NO_3^- loss by denitrification at 15 bar moisture tension and 20°C. Similar results have been reported by McGarity (1961).

Greenwood (1961) showed that the changeover from aerobic to anaerobic respiration by soil facultative anaerobes occurs at an approximate O_2 concentration of 10^{-6} M. Meek and Grass (1975) concluded that redox potential is a good indicator of the oxygen status of soil. In soils treated with NO_2-N, NO_3-N, fresh organic matter and an atmosphere of He, redox potential decreased and stabilized at +200 mV until all the NO_3^- had disappeared, then at +180 mV until all the NO_2^- was reduced (Bailey and Beauchamp 1973).

Temperature is a prime factor controlling the rate of denitrification. The lower temperature limit for denitrification has been set at 2°C (Bremner and Shaw 1958), at 3°C (Nommik 1956), and at 5°C (Bailey and Beauchamp 1973). Smid and Beauchamp (1976) concluded by extrapolation of rates at 5°, 10°, 15°, and 30°C however, that denitrification could occur at or near 0°C. Cho et al. (1979) measured denitrification intensities of some southern Alberta soils. Using a mathematical formula based on N_2 Production in incubated soils, they concluded that the minimum temperature for denitrification was 2.75°C. The upper temperature limit ranges from 70°C (Bremner and Shaw 1958) to 85°C (Nommik 1956). The optimum temperature lies between 60° and 65°C (Nommik 1956; Bremner and Shaw 1958).

Stanford et al. (1975) describe the response of the rate of denitrification to change in temperature by the temperature coefficient, Q_{10} (Q_{10} = x where x = x-fold increase in the rate of reaction for every 10°C increase in temperature). The range of temperature over which the denitrification $Q_{10}=2$ was 11° to 35°C. The most rapid decline in rate occurred when temperature was decreased from 10° to 5°C. Malhi (1978) observed a similar response of denitrification rate to temperature. In a Malmo SiCL, denitrification was detected at -4°C, and the most rapid increase in rate occurred below 10°C. The rate of denitrification continued to increase to 40°C, reaching a maximum of 71 ug N/g/day at 0 bar moisture tension.

Studies on the effect of soil pH on the rate of denitrification have shown that the optimum range is pH 7 to 8 (Jansson and Clark 1952; Nommik 1956). The lower and upper limits for denitrification were estimated at pH 5 and 10, respectively.

In addition to the edaphic factors already discussed, an available energy supply is a requirement for the denitrification process. Bowman and Focht (1974) increased the rate of denitrification in a soil by 58% when a 1000 ug/ml glucose solution was added. The rate of denitrification in a soil low in organic carbon is much slower than in a soil rich in organic matter (Khan and Moore 1968; Alexander 1977). Burford and Bremner (1975) observed high correlation between biological denitrification rate and total organic carbon ($r = 0.77$), and a very close correlation to water-soluble or easily mineralized carbon ($r = 0.99$). Similar results were shown by Stanford et al. (1975).

The presence of growing plant roots has a variable effect on the denitrification process (Woldendorp 1962; Bailey 1976; Stefanson 1976; Alexander, 1977). In the presence of a growing root system, the heterotrophic population is supplied with fresh organic matter in the form of root exudates and sloughed-off material. Respiration by the decomposing bacteria as well as by the growing roots reduces the oxygen supply in the root vicinity, favoring the denitrification process. The effect of this decreased oxygen content on denitrification will depend on supply of NO_2^- and NO_3^-. In a soil rich in mineral N, one would expect an increase in gaseous losses of N, but where N is scarce, the competition for this nutrient by the plants and the soil microflora may limit its availability for denitrification.

The nitrifying organisms are strict aerobes. Prolonged periods of anaerobic conditions will stop nitrification, as well as impede ammonification. Therefore, the level of NO_3-N available for denitrification would be limited. Reddy and Patrick (1975) concluded that in a soil where redox potential falls sufficiently to allow denitrification to occur, the most nitrification and denitrification occurred under two day aerobic and two day anaerobic cycling.

2.4 Leaching Losses of Nitrogen

Downward movement of soil or fertilizer N beyond the root zone is of agronomic importance because of the reduction in available quantity of this essential crop nutrient, and environmentally important because of possible NO_3-N pollution of ground or surface waters (Harmsen and Kolenbrander 1965; Viets 1965). There are two major processes involved in the movement of N through the soil:

(1) movement of dissolved or suspended material due to mass flow of the soil solution, and

(2) molecular or ionic diffusion due to concentration gradients (Gardner 1965).

In losses due to leaching, the primary mode of movement is by the process of convection by mass flow.

The leaching of N through agricultural soils is most frequently equated to the movement of NO_3-N. Although NO_2^-, urea and some other amino compounds are quite soluble in water, their existence in the soil solution is generally short-lived (Harmsen and Kolenbrander 1965). Because of its anionic form, NO_3^- is generally not adsorbed by soil colloids.

Workers studying the movement of NO_3-N through the soil have used several approaches. Leachate collected in lysimeter experiments in which field conditions were simulated have been analyzed over a period of years. Attempts to draw N balance sheets for ingoing and outgoing N were reviewed by Allison (1955). Some workers used an accompanying anion such as chloride (Cl^-) (Wetsellar 1961, 1962; Yimprasert and Blevins 1976) to trace NO_3^- movement through soils because of a similar leaching rate. Recovery of different ratios of the ions indicated a net increase in NO_3^- due to nitrification, or net decreases due to plant uptake, microbial immobilization or dissimilatory reduction. A third method of study has involved the use of isotopic N (Chalk and Kenney 1975; Malhi 1978). Cost of isotopic forms of N makes this an expensive method to study leaching losses under field conditions. It is superior however, in that quantitative analyses can be made to differentiate actual losses of applied N by leaching from losses from the soil due to uptake or reduction.

Allison (1955) reviewed results of 156 lysimeter experiments conducted in the United States. Averages of 25% to 60% of NO_3-N losses were attributed to leaching. Wetsellar (1962) documented substantial movement of NO_3^-

through coarse-textured soils. Rainfall sufficient to wet soil to a depth of 60 cm resulted in downward movement of NO_3-N of 65 cm. He concluded that the enhancement was due to channels left by partly decomposed plant roots.

Summerfallowing in the Prairie Provinces has resulted in deeper penetration of NO_3-N than occurred prior to cultivation. Studies in Manitoba by Michalyna (1959) show that subsoil NO_3-N increased with summerfallowing frequency. On a two year rotation of wheat-fallow forty years old, Rennie et al. (1976) found that the NO_3-N content to a depth of 4 m averaged approximately 500 kg N/ha. They suggested that 10% to 15% of the N mineralized in Saskatchewan since the beginning of cultivation has been leached beyond the root zone. In a single year however, Malhi (1978) found only insignificant amounts of labelled N below a depth of 60 cm when applied on a summerfallowed Orthic Black Chernozemic SiCL.

2.5 Effect of Method of Placement on Nitrification

If nitrification of urea and NH_4-based fertilizers can be slowed or delayed, recovery of fall-applied N in spring may be increased due to reduced losses of NO_3-N. Spring application of nitrogenous fertilizers may also be more efficient if nitrification were delayed until crop demand for N increased.

The maximum tolerable concentration of NH_4^+ for nitrification to occur varies from approximately 400 ug N/g soil (McIntosh and Frederick 1958; Anderson and Boswell 1964) to 800 ug/g (Broadbent et al. 1957), depending on soil pH which affects the $NH_4^+ \rightleftharpoons NH_3$ balance. Band-placement of ammoniacal fertilizers results in high concentrations of NH_4^+, NH_3 and soluble salts. Nitrification occurs in the diffuse zone where the local concentration of the slowly moving NH_4^+ decreases. The total amount of NO_3-N formed per unit area decreases beyond some point toward the center of the band, as the concentration of NH_4^+ increases (Wetsellar 1972).

Accompanying nitrification is a characteristic decrease in soil pH (Pang et al. 1975b). Consequent reduction in nitrification has been observed by Gasser (1965), Leitch (1973) and Malhi (1978). Therefore both the localized high salt concentration (Wetsellar 1972) and low pH in the fertilizer band may contribute to an environment unfavorable for continuing nitrification when N is banded at high rates. Although Malhi (1978) found no differences in yield of barley fertilized by banding or incorporating urea in spring, band-placement in fall increased the crop yield by 170 kg/ha over incorporated urea.

2.6 Nitrification Inhibitors

Nitrification inhibitors may increase the efficiency of ammoniacal fertilizers by reducing N losses due to leaching of NO_3-N and denitrification (Wagner and Smith 1968). The reduction of these losses may permit fall application of N fertilizers in regions where this practice would not otherwise be economically feasible because of over-winter losses (Walsh 1977).

The capability of a wide variety of chemicals to inhibit the function of nitrifying bacteria has been studied. These include not only compounds specifically formulated to inhibit nitrification, but also herbicides, fungicides, fumigants and compounds which simultaneously supply some N to the soil-crop system (Prasad et al. 1971). Most current research is involved with specific chemicals which impede or delay nitrification.

Bundy and Bremner (1973) compared 24 compounds for effectiveness in inhibiting nitrification on three different soils at 15°C and 30°C. N-Serve, ATC, and sodium or potassium azide were the most effective at 30°C. Variation in soil characteristics, especially temperature, produced variable results. Almost all inhibitors were more effective at 15°C than at 30°C. At the lower temperature, ATC was the most effective, preventing more than 90% of the nitrification which occurred in a soil with no inhibitor in 28 days. In areas of northern Idaho where yields of winter wheat did not respond to fall application of 84 kg N/ha as calcium nitrate, Huber et al. (1969) increased yield by 37% to 42% by using ammonium sulphate with N-Serve in the fall. Ammonium sulphate applied in fall without N-Serve produced intermediate yields. Crop utilization of fall-applied N was increased from 35% to 80% with the use of N-Serve.

Formulations such as N-Serve, ATC and thiourea are expensive however, and not clearly economical for general use in western Canadian agriculture at present. Less expensive volatile sulphur compounds are also recognized for their inhibition of nitrification (Powlson and Jenkinson 1971; Bremner and Bundy 1974). Carbon disulphide, dimethyl disulphide, methyl mercaptan, dimethyl sulphide and hydrogen sulphide have been shown to inhibit nitrification in a closed system (Bremner and Bundy 1974). They noted that carbon disulphide was less expensive and more effective than some patented formulations including N-Serve.

2.7 Fall versus Spring Application of Nitrogen Fertilizers

Fall application of N fertilizers has advantages previously discussed for both the farmer and the fertilizer industry. Research using actual and simulated field conditions to test the relative effectiveness of fall N fertilization is increasing in response to the increasing demand for this information by both farmers and the fertilizer industry.

Widdowson et al. (1961) and Devine and Holmes (1964) found inferior results from fall compared to spring application of N at Rothamsted in England. Similar results were reported by Olsen et al (1964) working in north-central Georgia. A three year study in Illinois by Welch et al. (1966) suggested that 1.5 kg of N applied in fall was needed to produce the same yield of wheat as one kg of N applied in spring. Spring application of ammonium nitrate, urea and anhydrous ammonia on four field plots in Ontario produced 18% greater yields of corn grain than equivalent fall application of these fertilizers (Stevenson and Baldwin 1969). Fall application of N was also shown to be inferior to spring application for the production of corn grain in Kentucky (Miller et al. 1975, Frye 1977).

Some workers have found fall application to be as effective as spring application. Tests by Larson and Kohnke (1946) in Indiana, showed that there was no significant difference in yield and protein content of corn whether fertilized with N in spring or fall. Similar results have been observed in Georgia (Boswell 1974; Boswell et al. 1974), and in Wisconsin using anhydrous ammonia (Chalk et al. 1975). Summarizing results of 22 field trials conducted in the Prairie Provinces between 1950 and 1968, McAllister (1969) reported that at 15 of the locations there were no differences in yield of cereal grain due to time of application, at 3 locations fall application was superior, and at 4 locations spring application proved superior to fall application. In 10 field trials located across the Prairie Provinces in fall, 1976, there were no significant differences in yield of wheat due to time of application of anhydrous ammonia, urea or ammonium nitrate (Harapiak 1979a). Average data from seven trial sites in Alberta indicated that in areas where soil moisture was limited in spring, fall application of N by banding resulted in higher yields of barley than banding in spring (Harapiak 1979b).

Under the climatic conditions of the Prairie Provinces where the soil remains frozen for most of the winter, it was previously believed that over winter losses of mineral N would be small. Leitch and Nyborg (1972) have shown however, that N uptake from fall applied N was about half that from spring applied N. Malhi and Nyborg (1974) reported that spring application of urea, ammonium nitrate and calcium nitrate increased the yield of barley grain an average of 530 kg/ha over fall, application of these fertilizers. In 10 field experiments, an average of 38% of fall applied urea N was lost from the mineral N pool over winter (Malhi 1978). Spring application of urea resulted in an additional 1,000 kg/ha grain yields, and twice the N uptake, compared to fall application. Field experiments conducted in Saskatchewan by Paul and Rennie (1977) demonstrated superiority of spring over fall N fertilization. Paul and Victoria (1978) used N-15 tagged fertilizer N to show that 20% of fall-applied N was taken up by the crop, with an additional 10% to 30% immobilized by the soil. Spring application resulted in uptake of 30% by the crop and 35% to 45% by soil micro-organisms. Partridge and Ridley (1974) reported an average of 15% higher yield of barley from spring rather than fall application of N on 13 well drained soils, and 56% higher yields at sites on imperfectly drained soils in Manitoba.

The use of nitrification inhibitors has been shown to decrease over winter losses of fall applied N in England (Gasser 1965) and in the United States (Huber et al. 1969;

Huber and Watson 1972; Boswell 1974; Frye 1977). In Central Alberta and Saskatchewan, band placement of urea or ammonium sulphate reduced over winter losses. The accompanying use of nitrification inhibitors including ATC and thiourea reduced losses further, but the highest yields of barley grain were obtained by spring application of N fertilizers (Malhi 1978).

2.8 Summary of Literature Review

Soil organic matter and chemical fertilizers are the sources of NH_4-N in the soil. Nitrifying bacteria convert NH_4-N to NO_3-N, which is subject to losses by leaching and denitrification. Losses of N are therefore primarily a consequence of nitrification.

Several factors which influence the rate of nitrification have been reviewed. Maximum rates appear to occur in the temperature range of 25 to 35°C, but it has been shown to occur at temperatures as low as 1 to 2°C. Optimum moisture for nitrification is near 0.3 bar moisture tension, but it occurs at measurable rates at 15 bar moisture tension.

Nitrification rates can be suppressed by inhibition of the growth of nitrifying bacteria. This is accomplished by concentration of NH_4-N by band placement, or by the use of chemical inhibitors, or both. These methods have been shown to increase N recovery and crop yields when N was applied in the fall.

Several factors which influence the rate of denitrification have also been reviewed. The soil bacteria responsible for denitrification are heterotrophic. The rate of denitrification is therefore greatly influenced by the readily available organic carbon supply. Denitrification occurs under conditions of restricted aeration. Rates are therefore greatest under saturated conditions (0 bar moisture tension), but it has been measured in soils at 15 bar moisture tension. The optimum temperature for denitrification is near 65°C. The limits of temperature are from 2 to 4°C, to approximately 85°C.

Most soils have the potential to denitrify. This has been shown by incubating soils under conditions which favor denitrification. Consensus of opinion is lacking however, regarding the occurrence and extent of N loss due to denitrification in soils of the Prairie Provinces. Measurement of crop yields and N uptake from fall versus spring applied N fertilizers has also resulted in variable conclusions. There is also some disagreement among workers about the reasons for higher crop yields from spring than from fall-applied N, in areas where these results have been shown to occur.

3. MATERIALS AND METHODS

3.1 Preliminary Field Experiments, 1975-76

In December, 1975 four field plots were established to observe changes in the soil mineral N status from December to the following spring. Three of these plots were located on Lethbridge SiCL at the Canada Agriculture Research Station, Lethbridge, Alberta. Two of these were on untilled barley stubble, and the other on summerfallow. Of the stubble plots, one had received a single 10 cm irrigation the previous fall to simulate a heavy fall rainfall. This provided two soil moisture levels on adjacent stubble plots (Appendix, Figure A1 and Table A4).

The fourth preliminary field plot was established on an existing moisture x N rate experiment on soil mapped as Chin SL at the Vauxhall substation. This plot provided high and low inorganic N levels, in combination with high and low moisture contents. (For a more complete description of soils at these sites, see Appendix, Tables A1 to 4).

The four plots were sampled four times: December 28, 1975, February 24, April 2, and April 28, 1976. At each sampling time three cores were taken per treatment with a 2 cm diameter coring tube (king tube sampler). These cores were separated into five subsamples from 0-15, 15-30, 30-60, 60-90 and 90-120 cm, and the subsamples of each set of three cores were combined. After sampling, the holes were filled with topsoil, and marked with small stakes to avoid contamination of subsequent samples. Soil samples were air-dried at 25°C immediately, and ground to pass a 2 mm seive.

3.2 Main Field Experiments 1976-77

Field plot experiments were initiated in the fall of 1976 on a Brown Chin SL at Vauxhall, a Dark Brown Lethbridge SiCL at Lethbridge, and a Black Pincher C at two sites near Glenwood, Alberta. Nitrogen treatments applied were urea, ammonium nitrate, and calcium nitrate. The urea treatments were applied by broadcasting, and band placement with and without the nitrification inhibitor 4-amino-1,2,4-triazole hydrochloride (ATC) at 2% (weight basis). The other N fertilizers were applied by broadcasting (spread on soil surface), and incorporating to a depth of 10 cm with a rototiller. All fertilizers were applied at the rate of 60 kg N/ha (nitrogen present in the nitrification inhibitor ATC was taken into account). In the banded fertilizer treatments, the urea was placed in bands 5 cm deep and 23 cm apart, through double disc openers. To include soil moisture over winter as a variable, a portion of each plot was irrigated in late September to early October, 1976. A tank truck was used to apply 10 cm of water to simulate an autumn rainfall or irrigation. A dyke was built around the perimeter of the irrigated section of each plot and sufficient guard strips between these and the non-irrigated treatments were left to reduce the possibility of lateral movement of water to adjacent treatments. At all sites, the individual treatments were 1.8 m wide and 6.8 m long. Each treatment was replicated four times in a randomized block design, except the two irrigated treatments. These treatments were also replicated four times, but the irrigation necessitated their location in one area of each plot (Appendix, Figure A3).

The plots were sampled four times from fall, 1976 to spring, 1977 (Appendix, Table A5). The incorporated fertilizer treatments were sampled by taking three cores 4.2 cm x 120 cm, with a coring truck. The cores were separated into sections corresponding to depths of 0-15, 15-30, 30-60, 60-90, and 90-120 cm. The three samples from each depth were combined.

Prior to the spring sampling, the fertilizer bands were mixed to a depth of 10 cm with a rototiller. Samples of all treatments were then taken by coring.

All soil samples were stored at -10°C before they were air-dried at 25°C.

Immediately after the spring sampling, each plot received a blanket application of 20 kg each of K and S/ha. Fertilizers used were potassium sulphate and elemental sulphur. Spring N treatments were applied, and the plots were seeded to Galt barley (Hordeum vulgare L.) at a rate of 54 kg/ha (1 bu/ac.). Phosphorus was drilled-in approximately 2 cm beside and 2 cm below the seed at 20 kg P_2O_5/ha. The fertilizer used was treble superphosphate.

Throughout the growing season, plots were kept weed-free by spraying with 2,4-D, and by hoeing. Sprinkle irrigation was carried out as necessary, and rates were not recorded. In August, 1977, the plots were harvested after treatment subplots were trimmed in length with a mower to eliminate any border effects at the ends. Harvesting consisted of cutting approximately 5 m from each of the centre two rows of each treatment. The plant material was placed in cloth sacks and air-dried. The samples were then weighed and threshed with a stationary threshing machine. Representative samples of grain and straw were ground to pass a 2 mm seive.

3.3 Analytical Procedures

Ammonium and NO_3-N were extracted from soil samples by shaking in a 1:5 ratio of soil: 2N KCl solution for one hour. Extracts were analyzed by the steam distillation method described by Bremner and Keeney (1966). In these experiments, NO_2^- concentration was not considered significant and therefore not analyzed separately.

Soil reaction was measured with a pH meter using a glass electrode in water saturated paste. The extracts were used to determine electrical conductivity.

Organic carbon was estimated using the modified Walkley-Black method, outlined by Allison (1965).

Particle size analysis of soil samples was done by the hydrometer method (Bouyoucos 1962).

Measurements of bulk density of all of the soils and depths were not made. For the calculations of N/ha, bulk densities were assumed 1.3 for all soils at 0-15 cm, 1.4 at 15-30 cm, and 1.5 at 30-120 cm (Bole 1976)[2].

---

[2] Bole, J.B. 1976. Personal communication. Soil Scientist, Soils Section, Canada Agriculture Research Station, Lethbridge, Alberta.

All grain, straw and representative soil samples were analyzed for total N by the Kjeldahl-Gunning method (Bremner 1960). No modifications to include NO_2-N and NO_3-N were used.

Results were analyzed by analysis of variance for randomized block, and split plot designs. Differences between means were tested by using Duncan's multiple range test (Steel and Torrie 1960). Variability, when expressed as standard deviation was calculated as follows:

$$s = \sqrt{\frac{(x-\bar{x})^2}{n-1}}$$

where x = observation
$\bar{x}$ = mean of observations
n = number of observations.

3.4 ^{15}N Incubation Study

3.4.1 Experimental design

Bulk samples of a Malmo CL, and samples from each of a dryland and irrigated Lethbridge SiCL were collected from the 0-15 and 45-60 cm depths in January, 1977 (Appendix, Tables A1 and 2). These samples were kept frozen at -5°C until ready for use. The samples were thawed and passed through a 5 mm screen after they had been dried only to the point where this process was possible. Subsamples of each soil and depth were taken at this point for determinations of moisture retention when air-dried, at 1/3 bar moisture tension, and of the initial sample (Appendix, Table A13).

Fertilizer treatments applied were KNO_3 and $(NH_4)_2SO_4$ solutions calculated to apply 100 ug N/g soil (O.D. basis) at 10 atom % excess ^{15}N. The fertilizer solutions were added to the soils in a volume of 200 ml per 4 kg O.D. soil which was spread thinly on a plastic sheet. After thorough mixing, the soils were placed into square plastic pots (10 x 10 x 13 cm deep) at 500 g O.D. soil per pot. The potted soils were then further moistened to field capacity with purified water. Untreated samples were similarly treated before potting. The pots were covered with snap-on lids which had 1 cm holes plugged with cotton. This procedure was chosen to allow ventilation, but to slow evaporation during incubation.

The pots were randomized, and incubated at temperatures of $-1\pm.5°C$, and $+4\pm.5°C$. After 24 hours of incubation, one replicate of pots was removed from the -1°C incubation chamber, and immediately air-dried. These samples will be referred to as the zero-time samples. Two remaining replicates of each soil, depth, fertilizer treatment and incubation temperature were incubated for 90 days.

After incubation, all of the soil in each pot was thinly spread and air-dried. It was then ground to pass a 2 mm seive.

3.4.2 Analytical methods

Ammonium and (NO_2+NO_3)-N were determined by separate distillations of the same KCl extract (Bremner and Kenney 1966). The ammonia was collected in 0.05N boric acid.

Between each distillation, approximately 15 ml of re-distilled ethanol was distilled to prevent cross-contamination by any labelled ammonia. Immediately after quantification of ammonia by titration with 0.01N NaOH, the distillate was re-acidified with 1 ml 0.2N HCl. The collected samples from two distillations of each soil extract were combined, and evaporated to a volume of 1-2 ml using a warm sand bath. At this point, samples containing less than 0.5 mg N were spiked by adding 1 mg N as NH_4Cl solution. The samples were then evaporated to dryness in 6 ml shell vials.

All samples were also analyzed for Kjeldahl N to include NO_3^- and NO_2-N by treatment with acid permanganate and reduced iron. The distilled samples were re-acidified and evaporated to dryness in a similar procedure to that used for inorganic N, except that no spiking of these samples was necessary.

The collected samples of ammonium chloride were converted to N_2 by lithium hypobromite oxidation using the apparatus described by Porter and O'Deen (1977). Ratio analysis of the N_2 from NH_4-N, (NO_2+NO_3)-N and total N was performed on a Micromass 602C dual channel magnetic ratio mass spectrometer.

Current peaks generated by the mass ratios were translated into atom % abundance ^{15}N by the procedure described by McGill and Hruday (1981).

The concentrations of the fertilizer solutions were determined by steam distilling a diluted aliquot. The analyzed concentrations of the solutions were 2020 ug N/ml for the $(^{15}NH_4)_2SO_4$ solution, and 2035 ug N/ml for the $K^{15}NO_3$ solution.

Calculation of the enrichment of the fertilizer solutions from atom % abundance ^{15}N of a sample of diluted enrichment was carried out using the following equation:

$$EF = \frac{(QS + QU)\ (ADS) - (QS)\ (ASS)}{QU} - ASS$$

where EF = atom % excess ^{15}N in fertilizer solution
QS = quantity of spiking N (ug)
QU = quantity of unspiked N (ug)
ADS = atom % abundance ^{15}N in diluted sample
ASS = atom % abundance ^{15}N in spiking solution used to dilute sample.

The atom % excess ^{15}N of the fertilizers (EF) were 9.5539% for the $(^{15}NH_4)_2SO_4$ solution and 9.9389% for the $K^{15}NO_3$ solution.

Natural abundance of ^{15}N in the soils was assumed to be the same for NH_4-N, NO_3-N and total N. Therefore, the natural abundance for each soil and depth used was that of the total N samples which were not labelled, and not diluted with spiking solution (Appendix, Table A16).

The atom % excess ^{15}N of the N in the soil (ES) was calculated from the atom % abundance ^{15}N of the diluted samples using the following equation:

$$ES = \frac{(QS + QU)\ (ADS) - (QU)\ (ASS)}{QU} - ANS$$

where QS, QU, ADS and ASS are as previously defined,
and ANS = natural atom % abundance of ^{15}N in soil.

For samples not diluted with spiking solution, ES was calculated by:

$$ES = AUS - ANS$$

where AUS = atom % abundance ^{15}N of unspiked sample
ANS = as defined above.

(See Appendix, Tables A14 and 15 for calculated values of ES)

Calculation of fertilizer N recovered in labelled samples was carried out using the following equation:

$$X = \frac{ES}{EF} \times SN$$

where X = fertilizer N in sample (ug/g O.D. basis)
SN = sample N (ug/g O.D. basis)
ES and EF = as previously defined

Percent recovery of applied fertilizer was expressed as $\frac{\text{fertilizer N in sample}}{\text{fertilizer N added}} \times 100\%$

4. RESULTS

4.1 Preliminary Field Experiments.

A fall-irrigated stubble plot, a dryland stubble and a dryland fallow plot, all on a Lethbridge SiCL were sampled four times throughout the winter-spring of 1976. A fourth preliminary study plot located on a Chin SL at Vauxhall was the site of a moisture x N rate experiment on corn conducted the previous season. The treatments of this plot which were sampled were irrigation treatments (1) nil and (2) 10 cm water when matrix potential reached -400 mb, and fertilizer treatments (1) nil and (2) 270 kg N/ha as NH_4NO_3 applied in the spring of 1975. (See Appendix, Figures A1 and 2).

4.1.1 Over-winter changes in the level of soil mineral N in a stubble soil at Lethbridge.

To a depth of 120 cm, there was a decrease in the level of mineral N from January 1 to April 1, in both the fall-irrigated and non-irrigated stubble plots (Table 1). This decrease was also observed in the 0-30 and 0-60 cm depths, indicating that the reductions in the upper horizons were not simply due to movement of N into lower horizons. In the fall-irrigated plot, the reduction was 60 kg N/ha, and about 30 kg N/ha in the non-irrigated plot. This reduction was not continuous throughout the winter and early spring, however. There was an increase in the level of mineral N of 20 kg/ha and 15 kg/ha at the fall irrigated and non-irrigated plots respectively, during April (Table 1).

The levels of NH_4-N to 60 cm declined throughout the sampling period in the irrigated soil, but remained relatively constant in the non-irrigated soil (Figure 1). The decrease in the levels of mineral N recovered from January 1 to April 1, and subsequent increase during April were primarily due to changes in the levels of NO_3-N. In both plots, the level of NO_3-N increased from January to April 1, but only in the non-irrigated plot was there an increase in the total mineral N level. (Standard deviation (s) indicated on Figures 1, 2 and 3 was calculated as indicated in the previous chapter. The number of observations (n) at the Lethbridge plots were 3, and 4 at the Vauxhall plot.)

Table 1. Mineral (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in preliminary stubble plots at Lethbridge.

Approximate sampling date	0-15	0-30	0-60	0-120
	Non-irrigated stubble plot depth (cm)			
Jan. 1	15 ab*	25 bc	44 b	94 a
Mar. 1	14 ab	32 ab	56 a	98 a
Apr. 1	12 b	22 c	34 b	59 b
May 1	20 a	35 a	52 ab	84 ab
	Fall-irrigated stubble plot			
Jan. 1	19 a	38 a	62 a	120 a
Mar. 1	17 a	34 a	62 a	108 a
Apr. 1	16 a	23 b	36 b	60 c
May 1	17 a	30 ab	45 b	80 b

* means in any column within each plot are significantly different when not followed by the same letter (P = 0.05).

4.1.2 Over-winter changes in the level of soil mineral N in a fallowed soil at Lethbridge.

To a depth of 120 cm, 48 kg N/ha of the mineral N recovered January 1 was not recovered April 1 (Table 2). Similar to the trends in the previously discussed stubble plots, reductions in mineral N recovered from the fallow soil occur in all depths indicating that downward or upward movement of N was not a major effect. In contrast to the results from

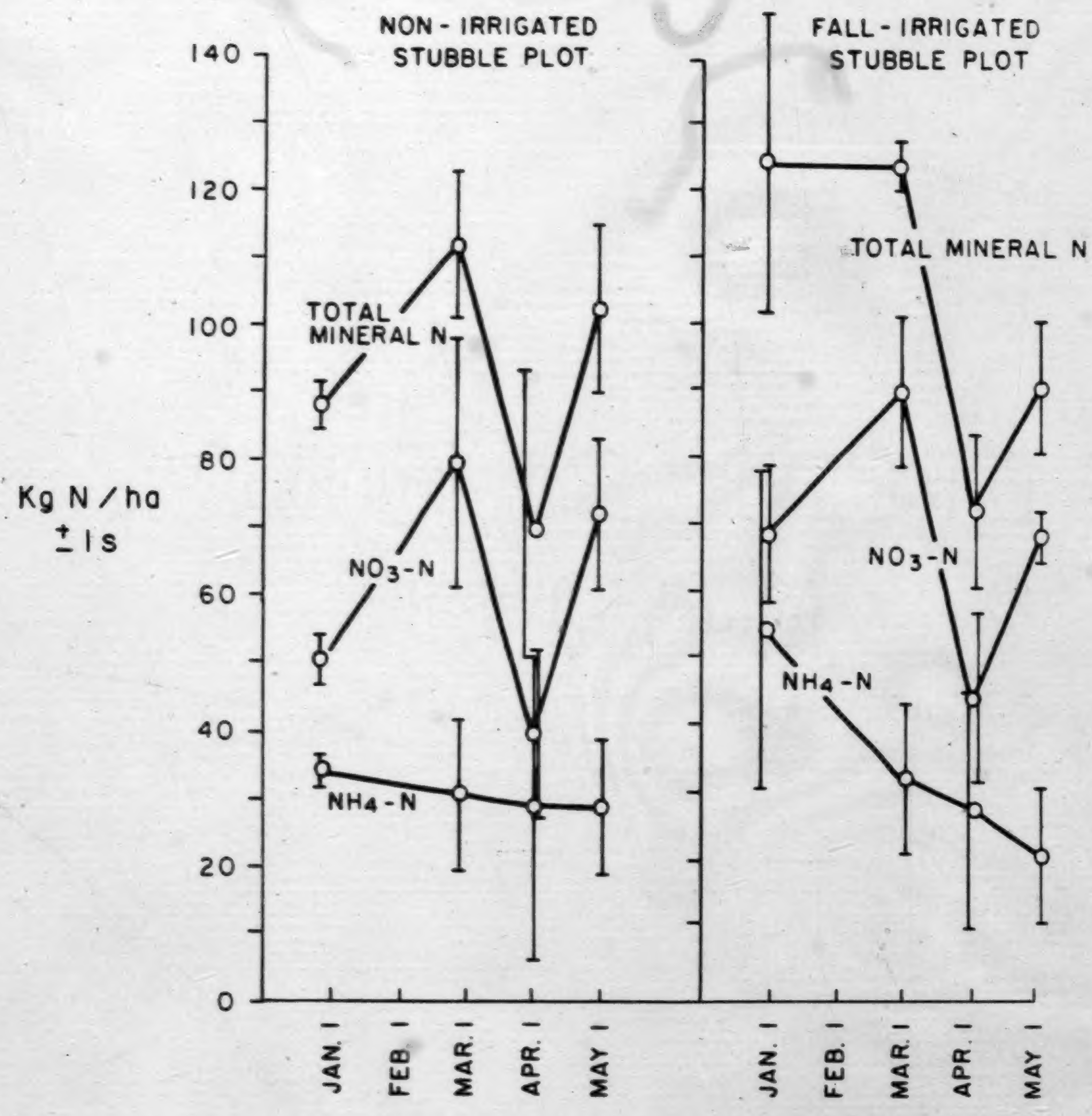


Figure 1. Over-winter changes in the level of soil mineral N to a depth of 60 cm in preliminary Lethbridge stubble plots.

the stubble plots, there was no increase in the level of NO_3-N from January to March. The levels of both NH_4-N and NO_3-N declined from January to March, followed by an increase in NO_3-N during April (Figure 2). Ammonium-N declined continually, from 50 kg in January, to 10 kg/ha by the end of April.

Table 2. Mineral (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in a preliminary summerfallow plot at Lethbridge

	depth (cm)			
Approximate sampling date	0-15	0-30	0-60	0-120
Jan. 1	37.0 a*	80.8 a	126.4 a	185.4 a
Mar. 1	32.0 ab	54.9 b	92.2 a	145.4 ab
Apr. 1	24.4 b	48.1 b	69.2 b	95.2 c
May 1	35.9 ab	66.6 ab	96.2 a	137.0 b

* means in any column are significantly different when not followed by the same letter (P=0.05).

The level of soil moisture (Appendix, Table A4) in the fallowed soil was near field capacity in the 15-60 cm depth. The field capacity was not determined, but an estimation can be made based on the proximity of the site from which the bulk samples for the incubation experiment were taken (Appendix, Table A13). In any case, the moisture level of the preliminary study plots at Lethbridge were not significantly greater than field capacity throughout the

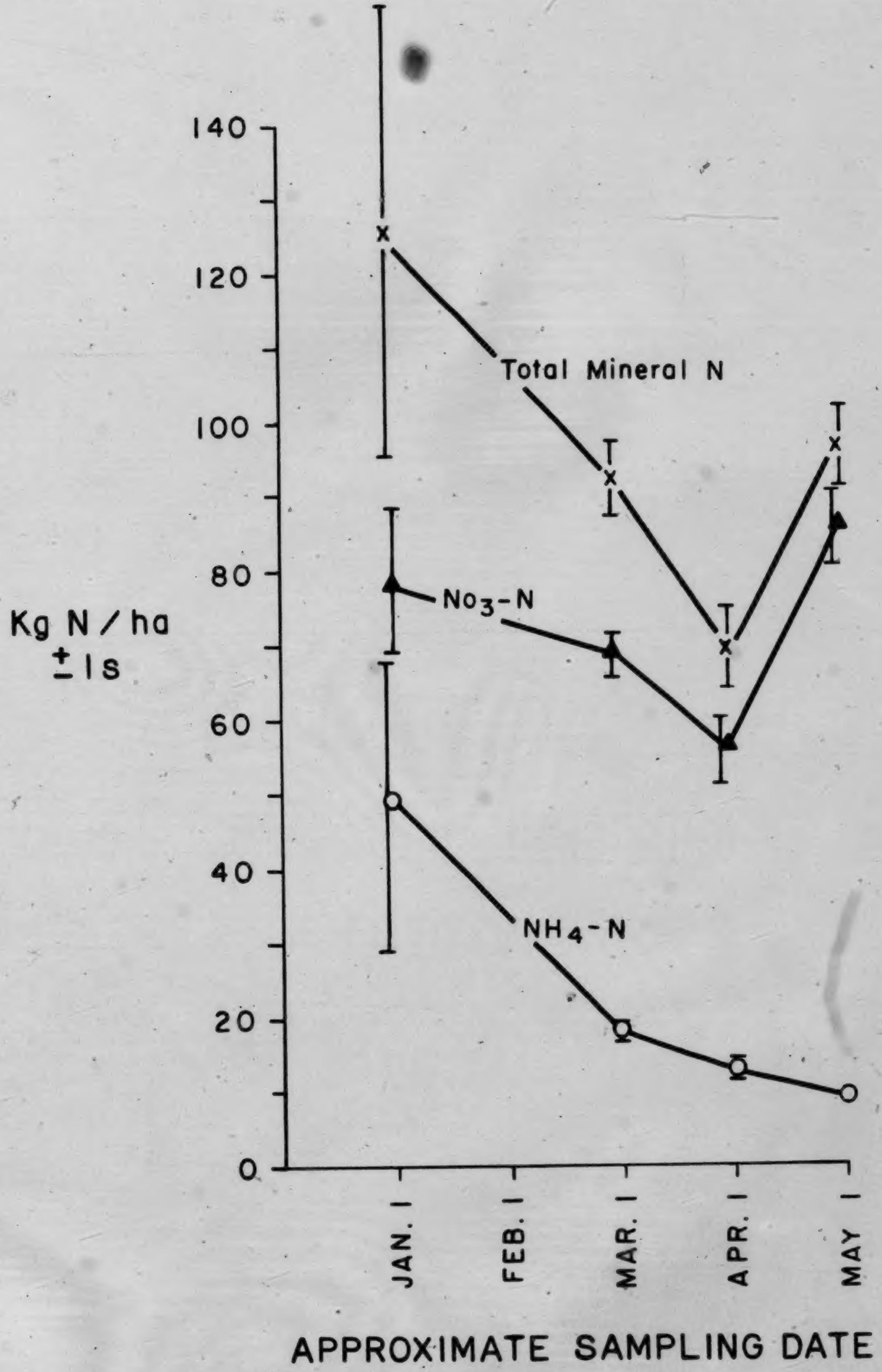


Figure 2. Over-winter changes in the level of soil mineral N to a depth of 60 cm at a Lethbridge preliminary fallow plot.

sampling period, and had completely thawed by April 1, 1976.

4.1.3 Over winter changes in the level of mineral N in a stubble soil at Vauxhall

Analysis of soil samples taken from the corn stubble site at Vauxhall revealed large accumulations of NO_3-N, beginning at depths of 30 to 90 cm (Appendix, Table A3). Soil moisture and mineral N levels were very variable, probably partly due to changes in soil texture within the plot and even replicates. The descriptive data presented in the Appendix, Tables A1 to 3 are average data from 4 replicates. The wide variations in the levels of recovered N between replicates, even to a depth of only 30 cm, place serious limitations on the usefulness of the data gathered at this site. The large differences between the levels of recovered N throughout the sampling period are not statistically significant (Table 3). The large standard deviations shown in Figure 3 are the result of the extremely variable nature of the soil at this site.

In spite of the variation noted, higher levels of mineral N were recovered from the subplots which had been fertilized with 270 kg N/ha in the spring of 1975 than from non-fertilized subplots (Figure 3). Also, of the fertilized subplots, higher levels of N were recovered from non-irrigated than from the irrigated subplots. These differences are not unexpected, and are most likely due to greater uptake of N from the fertilized irrigation treatment than from the fertilized, non-irrigated treatment by the previous corn crop.

Table 3. Mineral (NH_4+NO_3)-N (kg/ha) recovered over winter, 1976 in a preliminary stubble plot at Vauxhall**

Approximate sampling date	depth (cm) 0-15	0-30	0-60	0-120
	1. non-irrigated, non-fertilized			
Jan. 1, 1976	18 a*	31 a	90 a	220 a
Mar. 1	21 a	40 a	110 a	230 a
Apr. 1	20 a	33 a	87 a	180 a
May 1	17 a	34 a	87 a	180 a
	2. non-irrigated, 270 kg N/ha			
Jan. 1	120 a	170 a	260 a	420 a
Mar. 1	74 ab	120 a	240 a	370 a
Apr. 1	60 b	140 a	220 a	340 a
May 1	52 b	130 a	250 a	380 a
	3. irrigated, non-fertilized			
Jan. 1	24 a	39 a	110 a	280 a
Mar. 1	14 a	28 a	68 a	190 a
Apr. 1	16 a	24 a	59 a	180 a
May 1	15 a	25 a	52 a	140 a
	4. irrigated, 270 kg N/ha			
Jan. 1	28 a	59 a	160 a	360 a
Mar. 1	39 a	69 a	160 a	280 a
Apr. 1	32 a	66 a	170 a	340 a
May 1	27 a	46 a	120 a	240 a

* means in any column within any treatment are significantly different when not followed by the same letter (P=0.05).

** fertilizer treatments had been applied in spring, 1975.

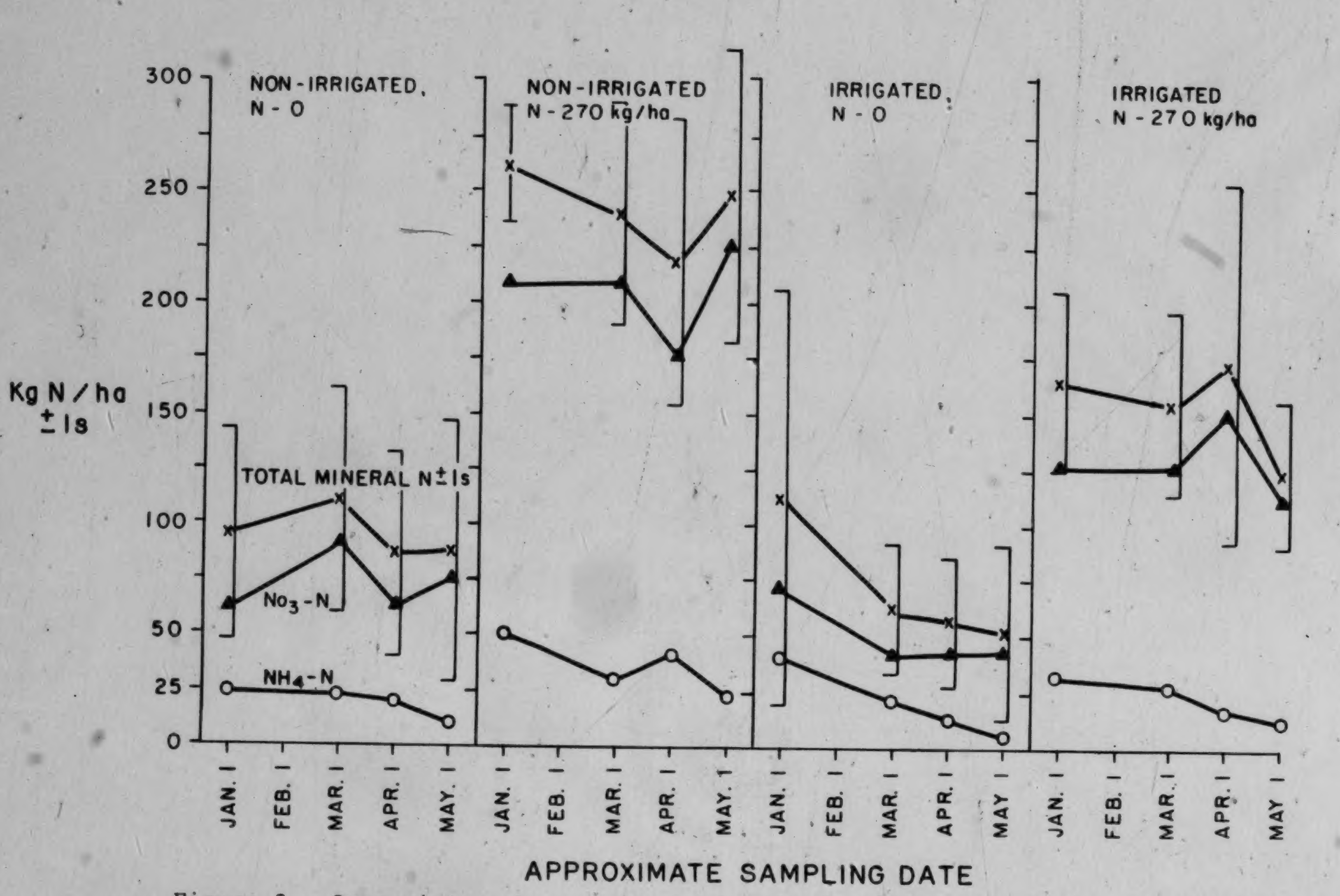


Figure 3. Over-winter changes in the level of soil mineral N to a depth of 60 cm in a preliminary Vauxhall stubble plot.

4.2 Main Field Experiments

In October 1976, field experiments were initiated at three locations to compare fall to spring application of different forms of fertilizer N in terms of yield of barley and N uptake, to assess the effectiveness of band placement of urea with and without the use of a nitrification inhibitor, to investigate the effect of soil moisture on the fate of fall applied calcium nitrate, and to compare the effects of these treatments on dryland and irrigated soils. Locations chosen were Vauxhall, Lethbridge and Glenwood, to include the Brown, Dark Brown and Thin Black soil zones of southern Alberta. At each location, sets of two plots were established, one on dryland and the other on a site which had been irrigated for a number of years. A portion of each of the six plots was irrigated in fall, 1976. An application of 10 cm of water was made to provide a higher soil moisture content before the onset of winter.

All fertilizers were applied at the rate of 60 kg N/ha. In late October, treatments applied by broadcasting and incorporation were urea, ammonium nitrate and calcium nitrate. Calcium nitrate was also applied in this manner on the fall-irrigated section of each plot. Urea was also applied in fall by band placement with and without the use of the nitrification inhibitor ATC. The inhibitor was included in the formulation at the rate of 2%, weight basis.

At the end of April, 1977, all of the plots were tilled with a roto-tiller, soil samples were taken, and the spring fertilizer treatments were applied. Urea, ammonium nitrate and calcium nitrate were applied by broadcasting and incorporating. The entire plot was then seeded to Galt barley (Hordeum vulgare L.) at the rate of 54 kg/ha. Plots at the irrigated sites were irrigated as required throughout the growing season.

4.2.1 Effect of fall vs spring broadcast-applied N on yield of barley and N uptake.

Spring broadcast application of urea, ammonium nitrate or calcium nitrate did not result in significantly higher yields of barley grain than did fall-application (Table 4). The average yields of barley from fall and spring broadcast application of the three N sources at the dryland sites were 1.01 and 1.20 t/ha at Vauxhall, .83 and .80 t/ha at Lethbridge, and 1.80 and 1.66 t/ha at Glenwood. At the dryland sites at Vauxhall and Lethbridge, severely limited soil moisture and growing season rainfall prevented responses to N fertilizer treatments (Appendix, Tables A8 and 11). Soil moisture at the dryland site at Glenwood was only slightly less limiting.

The interaction of time of application and N source was not significant at any site (complete data presented in Appendix, Table A7.). To examine the effect of time of application, the N sources were combined (Tables 4, 5 and 6).

At the irrigated sites, the average yields from fall and spring broadcast-applied N were 6.49 and 6.67 t/ha

Table 4. Yield of barley grain (t/ha) with fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$

Time of application	Dryland Sites Vauxhall	 Lethbridge	 Glenwood
Fall	1.01±.17*	.83±.16	1.80±.04
Spring	1.20±.27	.80±.06	1.66±.20
Control	.91	.64	1.39

	Irrigated Sites Vauxhall	 Lethbridge	 Glenwood
Fall	6.49±.18	5.37±.11	2.45±.39
Spring	6.67±.60	5.18±.08	2.75±.17
Control	5.59	5.02	1.02

* number of observations (n) for each mean = 12

at Vauxhall, 5.37 and 5.18 t/ha at Lethbridge, and 2.45 and 2.75 t/ha at Glenwood. None of these differences was significant.

At the irrigated sites at Vauxhall and Lethbridge, large subsurface accumulations of NO_3-N beginning at 60-90 cm greatly reduced responses to fertilizer N treatments (Appendix, Table A6). The unfertilized yields at the Vauxhall and Lethbridge irrigated sites were very high: 5.59 and 5.02

t/ha, respectively (Table 4). The shallow Chin profile at Vauxhall also varied greatly in texture. Although soil moisture was not a growth-limiting factor at the irrigated sites, these accumulations of NO_3-N presented difficulties in observations of crop response to fertilizer N treatments.

Responses to N by both yield (Table 4) and N uptake (Tables 5 and 6) are relatively larger at the irrigated site at Glenwood, than at the irrigated sites at Vauxhall and Lethbridge because of lower levels of soil N (Appendix, Table A6). The growth of barley at Glenwood may have been restricted somewhat by competition from weeds and volunteer grain during the early growing season. (The volunteer grain was removed from between the rows in early July.)

Nitrogen content of barley grain showed a slightly greater response to fertilizer N than did yield (Table 5). However, there were no significant differences between increases due to fall and spring application of N fertilizers, even though fertilizer N resulted in greater N uptake at all sites (Tables 5 and 6). The smallest, or almost no response to N was exhibited by the irrigated site at Lethbridge, where the subsoil accumulation of NO_3-N was the greatest. The standard deviation of the means of both grain yield (Table 4) and N content of grain (Table 5) are relatively lower than the means of total N uptake (Table 6). The reason is not clear, but it appears that yield and N content of grain may not be closely correlated to N content

Table 5. Nitrogen content of barley grain (kg/ha) from fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$

Time of application	Dryland Sites Vauxhall	 Lethbridge	 Glenwood
Fall	22.9±4.1*	18.2±4.1	38.4±1.4
Spring	30.1±6.1	19.2±1.5	35.3±4.5
Control	17.9	13.5	26.4

	Irrigated Sites Vauxhall	 Lethbridge	 Glenwood
Fall	139.9±1.9	121.1±4.9	34.3±4.9
Spring	141.8±12.5	119.8±3.1	38.2±1.6
Control	114.7	116.8	16.0

* number of observations (n) for each mean = 12

of the total above-ground crop. At the Vauxhall dryland site, it would appear that the difference between fall and spring application may be significant as measured by N content of grain. The large standard deviation of the means from that site completely obscure the difference however, if compared in terms of total N uptake (Table 6).

Table 6. Nitrogen uptake (kg/ha) by grain plus straw from fall and spring broadcast-applied urea, NH_4NO_3 and $Ca(NO_3)_2$

Time of application	Dryland Sites Vauxhall	 Lethbridge	 Glenwood
Fall	32.9±17.3	32.4±12.6	49.2±15.5
Spring	37.0±17.8	33.9±13.3	44.6±10.8
Control	24.9	31.2	32.4
	Irrigated Sites Vauxhall	 Lethbridge	 Glenwood
Fall	187.9±22.3	159.1±13.1	43.2±7.9
Spring	191.0±24.8	155.0±15.2	47.0±9.8
Control	155.3	151.0	20.5

* number of observations (n) for each mean = 12

4.2.2 Effect of N-source on yield of barley, N uptake, and mineral N recovered in spring.

The yields of barley at the dryland sites were not significantly different due to N-source broadcast-applied in spring or fall (Table 7). The variable nature of the soil resulted in the requirement of large differences for significance. However, at the Vauxhall and Lethbridge sites, yield was lower from urea than from NH_4NO_3 or $Ca(NO_3)_2$ when applied in the fall or spring. At the Vauxhall irrigated site, urea applied in spring resulted the highest yield, and the other N sources yielded similar yields, when applied in fall or spring. At both the Lethbridge and Glenwood irrigated sites, NH_4NO_3 tended to be better when applied in fall.

At the irrigated site at Vauxhall, urea resulted in the highest yield, and the lowest yield was fertilized with NH_4NO_3 (Table 7). There were no consistent significant differences in yield of barley or N uptake by grain due to N source at the irrigated sites, and the interaction of time of application and N source was not significant.

At the dryland sites, the N content of the barley grain was not significantly different due to N source (Table 8). At all three sites however, urea resulted in the lowest N content of the N sources when applied in fall or spring. This trend was not clear at the irrigated sites, but did occur somewhat at Glenwood. Urea applied in the spring resulted in the highest N content in the grain at the Vauxhall irrigated site, and this was significantly greater than from NH_4NO_3 or $Ca(NO_3)_2$ applied in spring.

Nitrogen uptake by the above-ground crop (Table 9) was significantly lower from urea only at the Vauxhall dryland site. Urea resulted in slightly lower uptake at the Glenwood dryland site, but only when applied in spring.

Table 7. The effect of fall and spring broadcast-applied N sources on yield of barley grain (t/ha) at dryland and irrigated sites.

			Dryland Sites	
Time of application	N source	Vauxhall	Lethbridge	Glenwood
fall	urea	.84 a*	.62 a	1.80 a
	NH_4NO_3	1.02 a	.93 a	1.77 a
	$Ca(NO_3)_2$	1.17 a	.83 a	1.85 a
spring	urea	.89 a	.74 a	1.46 a
	NH_4NO_3	1.35 a	.84 a	1.86 a
	$Ca(NO_3)_2$	1.37 a	.84 a	1.66 a
	control	.91	.64	1.39
			Irrigated Sites	
		Vauxhall	Lethbridge	Glenwood
fall	urea	6.52 ab	5.30 a	2.24 a
	NH_4NO_3	6.30 b	5.50 a	2.90 a
	$Ca(NO_3)_2$	6.65 ab	5.31 a	2.22 a
spring	urea	7.36 a	5.04 a	2.60 a
	NH_4NO_3	6.26 b	5.34 a	2.80 a
	$Ca(NO_3)_2$	6.41 b	5.17 a	2.89 a
	control	5.59	5.02	1.02

* means in any column within each site are significantly different when not followed by the same letter (P=0.05).

Table 8. The effect of fall and spring broadcast-applied N sources on N content of barley-grain (kg/ha) at dryland and irrigated sites.

		Dryland Sites		
Time of application	N source	Vauxhall	Lethbridge	Glenwood
fall	urea	19 a*	15 a	37 a
	NH_4NO_3	23 a	23 a	39 a
	$Ca(NO_3)_2$	27 a	17 a	40 a
spring	urea	19 a	17 a	30 a
	NH_4NO_3	30 a	20 a	39 a
	$Ca(NO_3)_2$	30 a	19 a	35 a
	control	18	13	26
		Irrigated Sites		
		Vauxhall	Lethbridge	Glenwood
fall	urea	139 ab	122 a	31 a
	NH_4NO_3	139 ab	125 a	40 a
	$Ca(NO_3)_2$	142 ab	116 a	32 a
spring	urea	155 a	116 a	36 a
	NH_4NO_3	131 b	122 a	39 a
	$Ca(NO_3)_2$	138 ab	120 a	39 a
	control	115	117	16

* means in any column within each site are significantly different when not followed by the same letter ($P=0.05$).

Table 9. The effect of fall and spring broadcast-applied N sources on N uptake by barley grain plus straw (kg/ha) at dryland and irrigated sites.

Time of application	N source	Dryland Sites		
		Vauxhall	Lethbridge	Glenwood
fall	urea	27 b	30 a	50 a
	NH_4NO_3	33 ab	37 a	48 a
	$Ca(NO_3)_2$	39 ab	31 a	54 a
spring	urea	28 b	35 a	42 a
	NH_4NO_3	42 a	34 a	49 a
	$Ca(NO_3)_2$	41 a	33 a	44 a
	control	25	22	32
		Irrigated Sites		
		Vauxhall	Lethbridge	Glenwood
fall	urea	187 a	160 a	38 a
	NH_4NO_3	186 a	161 a	51 a
	$Ca(NO_3)_2$	191 a	156 a	40 a
spring	urea	205 a	152 a	43 a
	NH_4NO_3	179 a	157 a	48 a
	$Ca(NO_3)_2$	188 a	155 a	49 a
	control	156	151	20

* means in any column within each site are significantly different when not followed by the same letter (P=0.05).

When total N uptake data for spring and fall-applied N sources are combined, an overall comparison of the sources at each site can be made (Table 10). Less urea-N was taken up than from NH_4NO_3 or $Ca(NO_3)_2$ at the Vauxhall dryland and Glenwood irrigated sites. At these two sites, $Ca(NO_3)_2$ was the best. There were no other significant differences between N sources at the dryland or irrigated sites.

The increases in N uptake due to fertilizer were 9, 14, and 14 kg N/ha for the urea, NH_4NO_3 and $Ca(NO_3)_2$ N sources, respectively, which is equivalent to 15, 23 and 23% of the N applied. At the irrigated sites, the increases in N uptake were 18, 21 and 21 kg N/ha from the three N sources, equivalent to 30, 35 and 35% of the N applied.

The levels of mineral N recovered in spring after fall broadcast-application of N sources are given in Tables 11a and 11b. Analysis of variance of the data including the control was made to indicate that the levels of N in the treated plots were not significantly greater than those in the control in every case.

At the Vauxhall and Lethbridge sites, the presence of high levels of subsoil NO_3-N places some question on the validity of the use of the subtraction method to determine recovery of fertilizer N. This is evident in Tables 11a and 11b, where levels of mineral N and fertilizer N to 60 cm depth are quite variable. Therefore, the levels of recovery should perhaps be viewed with caution.

Table 10. Average effect of fall and spring applied N-source on N uptake by grain plus straw (kg/ha).

	Dryland Sites		
N-Source	Vauxhall	Lethbridge	Glenwood
Urea	28 b	32 a	46 a
NH_4NO_3	38 a	36 a	48 a
$Ca(NO_3)_2$	40 a	32 a	49 a
Control	25	22	32
	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
Urea	196 a	156 a	40 b
NH_4NO_3	18[illegible] a	159 a	49 a
$Ca(NO_3)_2$	190 a	156 a	44 ab
Control	156	151	20

* means in each column are significantly different when not followed by the same letter (P=0.05).

At the dryland sites (Table 11a), less urea-N was recovered in spring than fertilizer N from the other sources. The exceptions were at Lethbridge, in the 0-15 cm depth, and in the 0-60 cm depth, where error resulting from soil variability was involved. The surface soil at Vauxhall and Lethbridge is slightly alkaline (pH 7.4 and 7.6, respectively). One might therefore suspect some loss

Table 11a. Levels of mineral N (kg/ha) recovered in spring, 1977 after fall broadcast-application of N sources at dryland sites.

		Depth (cm)					
Site	N-source	0-15	Fertilizer N	0-30	Fertilizer N	0-60	Fertilizer N
Vauxhall	control	22 c**		33 b		42 b	
	urea	46 b	24	63 ab	30	75 a	33
	NH_4NO_3	66 a	44	83 a	50	97 a	55
	$Ca(NO_3)_2$	55 ab	33	75 a	42	89 a	47
Lethbridge	control	14 c		29 b		79 b	
	urea	31 a	27	57 a	28	108 a	29
	NH_4NO_3	24 a	10	62 a	33	110 a	31
	$Ca(NO_3)_2$	24 a	10	62 a	33	98 ab	19
Glenwood	control	27 b		45 b		65 b	
	urea	59 a	32	79 a	34	106 a	41
	NH_4NO_3	64 a	37	92 a	47	120 a	55
	$Ca(NO_3)_2$	66 a	39	98 a	53	119 a	54
Mean	control	21		36		62	
	urea	45	24	64	28	96	34
	NH_4NO_3	51	30	79	43	109	47
	$Ca(NO_3)_2$	48	27	78	42	102	40

* fertilizer N = level of N in treatment - level of N in control, each the average of 4 replicates.

** means in any column at each site are significantly different when not followed by the same letter (P=0.05).

- complete recovery would be 60 kg/ha.

Table 11b. Levels of mineral N (kg/ha) recovered in spring, 1977 after fall broadcast-application of N sources at irrigated sites.

Site	N-source	Depth (cm) 0-15	Fertilizer N	0-30	Fertilizer N	0-60	Fertilizer N
Vauxhall	control	34 c**		79 c		142 c	
	urea	72 b	38	118 b	39	170 b	28
	NH_4NO_3	89 a	55	150 a	71	196 ab	54
	$Ca(NO_3)_2$	77 ab	43	148 a	59	210 a	68
Lethbridge	control	32 c		64 b		186 b	
	urea	51 a	19	95 a	31	201 ab	15
	NH_4NO_3	55 a	23	115 a	51	197 ab	11
	$Ca(NO_3)_2$	43 b	11	94 a	30	251 a	65
Glenwood	control	16 c		26 c		42 c	
	urea	28 b	12	48 b	22	68 b	26
	NH_4NO_3	42 a	26	72 a	46	94 a	52
	$Ca(NO_3)_2$	41 a	25	67 a	41	84 a	42
Mean	control	27		56		123	
	urea	50	23	87	31	146	23
	NH_4NO_3	62	35	113	57	162	39
	$Ca(NO_3)_2$	54	27	103	47	181	58

* fertilizer N = level of N in treatment - level of N in control, each the average of 4 replicates.

** means in any column at each site are significantly different when not followed by the same letter ($P=0.05$).

- complete recovery would be 60 kg/ha.

of urea-N by volatilization. The surface soil at the dryland site at Glenwood was slightly acidic however (pH 6.1), and the same trend occurred there. Therefore, volatile losses of urea-N stimulated by an alkaline soil reaction are not a probable explanation. Although investigations into the reason for lower urea-N recovery were beyond the scope of the present study, possible explanation may be the retention of NH_4-N by the clay fraction of these soils and/or differentiation in favor of NH_4-N during immobilization by soil bacteria.

At the dryland sites (Table 11a), if the variable data from the Lethbridge site are excluded, the recoveries of applied N to a depth of 60 cm were 62, 92 and 85 for urea, NH_4NO_3 and $Ca(NO_3)_2$, respectively. For all N sources, about 75% of recovered fertilizer N was in the 0-15 cm depth, and only an average of 4% of applied N was recovered in the 30-60 cm depth.

The recovery of fertilizer N in spring at the irrigated sites (Table 11b) to a depth of 60 cm was quite variable, but to a depth of 30 cm, less urea-N was recovered at all of the sites. (The difference at Lethbridge was not significant, however.) The pH of the surface soil at the irrigated sites at Vauxhall, Lethbridge and Glenwood was 7.0, 7.8 and 7.7, respectively. Because the broadcast-applied fertilizer was immediately well-mixed into the soil to 10 cm with a roto-tiller, it is not likely that volatile losses of urea-N occurred. The lower levels of recovery of urea-N were accompanied by subsequent lower N uptake at the Vauxhall dryland site, but not at the Vauxhall and Glenwood irrigated sites. Nitrogen uptake there was also not lower from fall-applied urea than from the other sources. This may be a further indication that urea-N may have been retained by the soil but later released for crop uptake, rather than lost by volatilization.

At all the dryland and irrigated sites, the recovery of $Ca(NO_3)_2$-N in spring and N uptake by the crop were not lower than from the other sources. This is an indication that higher losses of NO_3-N from $Ca(NO_3)_2$ did not occur over winter, than from NH_4NO_3 or urea.

4.2.3 Effect of band-placement of fall-applied urea, with and without the nitrification inhibitor ATC.

A comparison of methods used to inhibit nitrification was conducted to study their effects on yield and N uptake of barley. Urea was applied in fall by broadcasting, and by band-placement with and without the nitrification inhibitor ATC (2%, weight basis). Soil samples were taken in fall (before application) and in spring (before seeding). Ammonium and NO_3-N were analyzed to compare the effects of these methods on over winter nitrification of fertilizer N.

The method of application and the use of ATC did not have a significant effect on the yield of barley (Table 12), the N content of the grain (Table 13), or the crop uptake of N (Table 14) at the dryland sites at Vauxhall and

Lethbridge. Because yields did not respond to N at these sites due to extremely limited soil moisture and high soil N, yield differences resulting from placement over winter and nitrification inhibition would not be expected. At the dryland site at Glenwood the yield of grain responded significantly only when urea was applied by broadcasting (Table 12). The yields and N content of grain were similar whether or not ATC was included with band-applied urea (Table 13), but the total N uptake there (Table 14), was decreased by banding, and decreased somewhat further by the use of ATC (Table 14).

At the irrigated site at Lethbridge the yield was apparently repressed by the use of ATC with banded urea (Table 12). The reason for the lower yield from that treatment is not clear since only a low rate of ATC was used, and because the fall-applied bands were well mixed into the soil before seeding. The yield and N uptake results at the irrigated plot at Lethbridge were similar to those at the dryland site there, in that there were no significant responses to N at all. Therefore conclusions about methods of application cannot be made.

At the Vauxhall and Glenwood irrigated sites there were no significant differences due to method of application of urea (Tables 12, 13 and 14).

Band placement and the use of ATC did have a significant effect on the extent of nitrification, however (Tables 15a and 15b).

Table 12. Yield of barley grain (t/ha) with fall application of urea by broadcasting and band-placement with and without the nitrification inhibitor ATC.

	Dryland Sites		
Treatment	Vauxhall	Lethbridge	Glenwood
urea broadcast	.84 a*	.62 a	1.80 a
urea banded	1.09 a	.44 a	1.48 b
urea + 2% ATC banded	.95 a	.56 a	1.46 b
control	.91 a	.64 a	1.39 b

	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
urea broadcast	6.52 a	5.30 a	2.24 a
urea banded	6.60 a	5.34 a	2.40 a
urea + 2% ATC banded	6.23 a	4.48 b	2.56 a
control	5.59 b	5.02 ab	1.02 b

* means are significantly different when not followed by the same letter (P=0.05).

Table 13. Nitrogen uptake by grain (kg/ha) with fall application of urea by broadcasting and band-placement with and without the nitrification inhibitor ATC.

	Dryland Sites		
Treatment	Vauxhall	Lethbridge	Glenwood
urea broadcast	19 a*	15 a	37 a
urea banded	23 a	11 a	29 ab
urea + 2% ATC banded	21 a	13 a	30 ab
control	18 a	14 a	26 b
	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
urea broadcast	139 ab	122 a	31 a
urea banded	145 a	125 a	33 a
urea + 2% ATC banded	138 ab	113 a	36 a
control	115 b	117 a	16 b

* means in each column are significantly different when not followed by the same letter (P=0.05).

Table 14. Nitrogen uptake by grain plus straw (kg/ha) with fall application of urea by broadcasting and band-placement with and and without the nitrification inhibitor ATC.

	Dryland Sites		
Treatment	Vauxhall	Lethbridge	Glenwood
urea broadcast	27 a*	30 a	50 a
urea banded	34 a	29 a	42 ab
urea + 2% ATC banded	30 a	24 a	37 b
control	25 a	23 a	32 b

	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
urea broadcast	187 a	160 a	38 a
urea banded	201 a	162 a	41 a
urea + 2% ATC banded	190 a	151 a	44 a
control	155 b	151 a	20 b

* means in each column are significantly different when not followed by the same letter (P=0.05).

Table 15a. Recovery of NH_4-N, NO_3-N and (NH_4+NO_3)-N (kg/ha) at dryland sites in spring, from urea fall-applied by broadcasting, and banding with and without the nitrification inhibitor ATC.

		kg N/ha			
		0-15 cm			0-60 cm
Site	Treatment	NH_4-N	NO_3-N	Total	(NH_4+NO_3)-N
Vauxhall dryland	nil	5 c*	17 b	22 b	42 b
	broadcast	9 bc	38 a	47 a	75 a
	band	18 ab	32 ab	50 a	76 a
	band + ATC	28 a	20 b	48 a	69 ab
Lethbridge dryland	nil	6 b	8 b	14 b	79 a
	broadcast	6 b	25 a	31 a	109 a
	band	11 b	18 a	29 a	72 a
	band + ATC	22 a	9 b	31 a	63 a
Glenwood dryland	nil	14 a	13 c	27 b	65 b
	broadcast	23 a	35 a	58 a	106 a
	band	32 a	30 ab	62 a	101 a
	band + ATC	30 a	20 bc	50 a	90 ab

* means in any column within each site are significantly different when not followed by the same letter (P=0.05).

Table 15b. Recovery of NH_4-N, NO_3-N and (NH_4+NO_3)-N (kg/ha) at irrigated sites in spring, from urea fall-applied by broadcasting, and banding with and without the nitrification inhibitor ATC.

		kg N/ha			
		0-15 cm			0-60 cm
Site	Treatment	NH_4-N	NO_3-N	Total	(NH_4+NO_3)-N
Vauxhall irrigated	nil	4 b*	30 b	34 b	142 b
	broadcast	10 b	62 a	72 a	170 ab
	band	9 b	61 a	70 a	196 a
	band + ATC	30 a	38 b	68 a	170 ab
Lethbridge irrigated	nil	8 b	24 b	32 b	186 a
	broadcast	10 b	41 a	51 ab	200 a
	band	10 b	45 a	55 ab	225 a
	band + ATC	30 a	35 a	65 a	250 a
Glenwood irrigated	nil	9 b	7 b	16 b	42 b
	broadcast	9 b	19 a	28 ab	68 a
	band	12 b	22 a	34 a	71 a
	band + ATC	25 a	10 b	35 a	68 a

* means in any column for any site are significantly different when not followed by the same letter ($P=0.05$).

(Because of the irregular accumulations of soil NO_3-N at the Vauxhall and Lethbridge sites, and also because leaching was not expected to be extensive, a comparison of the levels of NH_4-N and NO_3-N in the 0-15 cm depth are shown.) At the dryland sites, nitrification between the time of appplication and spring was reduced by banding the urea, and further reduced by banding with ATC (Table 15a). The average recovery of fertilizer (NH_4+NO_3)-N in the surface depth was 24, 26 and 22 kg/ha at the dryland sites, from the broadcast, banded and banded with ATC treatments, respectively. The recovery of fertilizer N in spring was not significantly different due to inhibition of nitrification at the dryland sites.

At the irrigated sites (Table 15b) only the use of ATC with banded urea had a significant effect on nitrification. Nitrification was slowed somewhat by banding at the Glenwood site, but not significantly. At the irrigated sites the average recovery of fertilizer N to a depth of 15 cm was 26, 27 and 28 kg/ha from the broadcast, banded and banded with ATC treatments, respectively.

The soil at both the irrigated and dryland sites was dry throughout the sample period, although the surface soil at the irrigated sites was slightly more moist (Appendix, Table A8). Perhaps the reason for the difference in effectiveness of banding urea in the inhibition of nitrification was due to this slight difference in soil moisture. It is conceivable that nitrification could be restricted more by banding urea in a dry soil than in a more moist soil.

If it is assumed that urea applied in the fall by broadcasting was completely hydrolyzed by spring, then the data indicate that the urea in the fall banded treatments was also completely hydrolyzed. This is shown by the similar levels of mineral N recovered by analysis, regardless of method of application.

4.2.4 Effect of fall irrigation and fall applied $Ca(NO_3)_2$ on yield of barley, N uptake and recovery of fertilizer N in spring.

To study the effect of soil moisture in fall on over-winter transformations or losses of fall applied $Ca(NO_3)_2$, a portion of each of the dryland and irrigated plots was irrigated in fall. A depth of 10 cm water was applied to simulate irrigation or fall rainfall. Calcium nitrate was applied at 60 kg N/ha, by broadcasting and incorporating after the irrigated treatments had dried sufficiently to allow incorporation with a roto-tiller (4-6 days).

At the dryland sites the yield response to fall irrigation was greater than to the fall-applied fertilizer (Table 16). As was discussed earlier, limited soil moisture prevented a significant response to N. Even on the fall-irrigated treatments of the dryland sites, soil moisture during the growing season restricted the yield response to fertilizer N. Only at the Glenwood site was the fall irrigated and fertilized yield significantly higher than the irrigated, non-fertilized yield.

As expected, there was no significant yield response to fall irrigation at any of the irrigated sites (Table 16). Accumulations of NO_3-N and replicate variation at Vauxhall and Lethbridge, which were previously discussed, made differences in yield required for significance large. At the irrigated site at Glenwood, the yield response to fertilizer N on the fall irrigated treatment was similar in size to that on the treatments not irrigated in fall. In other words, NO_3-N added to moist soil in fall was as effective as NO_3-N applied on drier soil.

This N content of grain and crop uptake (Tables 17 and 18) indicate the same trends. At the dryland sites the N content of grain was increased by irrigation, but not by N. The N uptake by the above-ground crop at Vauxhall was also higher due to N with no fall irrigation. At the dryland site at Glenwood, N uptake was increased by fertilizer N to a greater extemt when fall irrigated than when not irrigated in fall.

At the irrigated sites there was no increase in N content of grain or N uptake due to fall irrigation. There was also no reduction in N content or uptake due to fall irrigation (Tables 17 and 18). The increase in N content and uptake due to fertilizer N was significant only at the Glenwood site.

Table 16. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on yield of barley (t/ha) at dryland and irrigated sites.

Fall treatment	Dryland Sites Vauxhall	 Lethbridge	 Glenwood
control	.91 b*	.64 b	1.39 c
$Ca(NO_3)_2$	1.18 b	.83 ab	1.85 bc
fall-irrigated control	2.36 a	1.28 ab	2.44 b
fall-irrigated + $Ca(NO_3)_2$**	2.69 a	1.49 a	3.40 a

	Irrigated Sites Vauxhall	 Lethbridge	 Glenwood
control	5.59 ab	5.02 b	1.02 b
$Ca(NO_3)_2$	6.65 a	5.31 ab	2.22 a
fall-irrigated control	5.10 b	5.64 ab	1.12 b
fall-irrigated +$Ca(NO_3)_2$	5.85 ab	5.72 a	2.39 a

* means are significantly different when not followed by the same letter (P=0.05).

** $Ca(NO_3)_2$ was broadcast and incorporated after fall irrigation.

Table 17. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on N content of barley grain (kg/ha) at dryland and irrigated sites.

Fall treatment	Dryland Sites		
	Vauxhall	Lethbridge	Glenwood
control	18 b*	13 c	26 c
$Ca(NO_3)_2$	27 b	17 bc	40 bc
fall-irrigated control	49 a	26 ab	46 b
fall-irrigated + $Ca(NO_3)_2$**	54 a	32 a	65 a

	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
control	115 ab	117 a	16 b
$Ca(NO_3)_2$	142 a	116 a	32 a
fall-irrigated control	96 b	131 a	17 b
fall-irrigated +$Ca(NO_3)_2$	122 ab	131 a	33 a

* means are significantly different when not followed by the same letter (P=0.05).

** $Ca(NO_3)_2$ was broadcast and incorporated after fall irrigation.

Table 18. Effect of fall irrigation and fall broadcast-applied $Ca(NO_3)_2$ on N uptake by grain plus straw (kg/ha) at dryland and irrigated sites.

Fall treatment	Dryland Sites		
	Vauxhall	Lethbridge	Glenwood
control	25 c *	22 b	32 c
$Ca(NO_3)_2$	39 b	31 ab	54 b
fall-irrigated control	61 a	34 ab	57 b
fall-irrigated + $Ca(NO_3)_2$**	71 a	45 a	82 a
	Irrigated Sites		
	Vauxhall	Lethbridge	Glenwood
control	156 ab	151 a	20 b
$Ca(NO_3)_2$	191 a	156 a	40 a
fall-irrigated control	121 b	171 a	22 b
fall-irrigated +$Ca(NO_3)_2$	167 ab	174 a	41 a

* means in any column are significantly different when not followed by the same letter (P=0.05)

** $Ca(NO_3)_2$ was broadcast and incorporated after fall irrigation.

The level of soil mineral N recovered from the unfertilized fall treatments at the dryland sites were not affected by fall irrigation (Table 19a). This indicates that the net effects of mineralization, immobilization and denitrification, if it occurred, were not affected by higher soil moisture. The recovery of fertilizer N was decreased at Vauxhall, increased at Lethbridge, and increased due to fall irrigation at Glenwood, although only the difference at Lethbridge was significant.

At the irrigated sites, the levels of mineral N extracted from the soil in spring from the fall treatments not fertilized were not different due to fall irrigation. Furthermore, the levels of fertilizer N recovered from fall treatments were not affected by fall irrigation. These results indicate that the levels of soil mineral N over winter were not affected by the levels of soil moisture, and secondly, that the recovery of fall-applied N was not reduced due to soil moisture. Supportive evidence of this are the previously discussed similar levels of yield and N uptake responses at the irrigated sites, regardless of fall irrigation (Tables 16, 17 and 18).

The levels of total and fertilizer mineral N are reported only for the 0-30 cm depth to avoid interference from the high levels of NO_3-N at the Vauxhall and Lethbridge sites. Leaching of much of the fertilizer N was not anticipated. Because the fall irrigation treatments were

Table 19a. Recovery of (NH_4+NO_3)-N and fertilizer N* (kg/ha) to a depth of 30 cm in spring, from fall-irrigated, and fall broadcast-applied $Ca(NO_3)_2$ treatments at dryland sites.

	Dryland Sites					
	Vauxhall		Lethbridge		Glenwood	
Fall treatment	(NH_4+NO_3) -N	Fertilizer N	(NH_4+NO_3) -N	Fertilizer N	(NH_4+NO_3) -N	Fertilizer N
control	33 b**	--	29 c	--	45 b	--
$Ca(NO_3)_2$	75 a	42	62 b	33	98 a	53
fall-irrigated control	40 b	--	30 c	--	49 b	--
fall-irrigated $+Ca(NO_3)_2$***	66 ab	26	92 a	62	106 a	57

---

* fertilizer N = treatment N - respective control N.

** means in any column are significantly different when not followed by the

*** $Ca(NO_3)_2$ at 60 kg N/ha was broadcast and incorporated after irrigation.

Table 19b. Recovery of (NH_4+NO_3)-N and fertilizer N* (kg/ha) to a depth of 30 cm in spring, from fall-irrigated, and fall broadcast-applied $Ca(NO_3)_2$ treatments at irrigated sites

	Irrigated Sites					
	Vauxhall		Lethbridge		Glenwood	
Fall treatment	(NH_4+NO_3) -N	Fertilizer N	(NH_4+NO_3) -N	Fertilizer N	(NH_4+NO_3) -N	Fertilizer N
control	79 b**	--	64 ab	--	26 b	--
$Ca(NO_3)_2$	148 a	69	94 a	30	67 a	41
fall-irrigated control	61 b	--	52 b	--	24 b	--
fall-irrigated $+Ca(NO_3)_2$***	126 a	66	92 a	40	68 a	44

* fertilizer N = treatment N - respective control N.

** means in any column are significantly different when not followed by the

*** $Ca(NO_3)_2$ at 60 kg N/ha was broadcast and incorporated after irrigation.

carried out before $Ca(NO_3)_2$ was applied, downward movement of NO_3-N in the fall irrigated treatments were expected to be much less than had irrigation followed fertilization. It is quite conceivable that some of the NO_3-N would have moved below 30 cm. Therefore, levels of fertilizer NO_3-N recovered from the 0-15, 15-30 and 30-60 cm depths are presented in Table 20.

These data were derived from mean levels (4 replicates) of NO_3-N in the 0-15, 0-30 and 0-60 cm depths. For example, NO_3-N in the 30-60 cm depth was calculated by subtracting NO_3-N (0-30 cm) from NO_3-N (0-60cm). Because these subtractions were made using the mean valves of 4 replicates, statistical verification by testing the differences was not valid. These data should therefore be viewed with care, and as trends only.

The data presented are a further indication that a decrease in the recovery of fertilizer NO_3-N due to fall irrigation did not occur. At the dryland sites, the fertilizer NO_3-N recovered in the 15-30 cm depth was similar, whether or not the soil had been irrigated prior to application. Perhaps the extent of leaching should be examined by comparing the levels of NO_3-N in the 0-15 depths across the treatments, and the total in the 0-60 cm depth. At both the dryland and irrigated sites, apparently more fertilizer NO_3-N was leached out of the 0-15 cm depth in the non-irrigated treatment than in the fall irrigated treatment. The total fertilizer N recovered to 60 cm

Table 20. Average recovery of fertilizer NO_3-N* (kg/ha) in spring, from fall-applied $Ca(NO_3)_2$ on fall irrigated and non-irrigated treatments at dryland and irrigated sites.

	Dryland Sites		Irrigated Sites	
Depth (cm)	not fall irrigated	fall irrigated	not fall irrigated	fall irrigated
0-15	27	36	27	40
15-30	15	12	20	10
30-60	8	2	12	19
Total	50	50	59	68

* fertilizer NO_3-N = treatment NO_3-N - respective control NO_3-N.

however, was not reduced due to fall irrigation. This is in agreement with the results presented in Tables 19a and 19b.

4.3 Recovery and Transformation of N-15-Labelled Fertilizers in a Soil Incubation Experiment.

Solutions of $(^{15}NH_4)_2SO_4$ and $K^{15}NO_3$ were added to moist samples of soil from the 0-15 cm and 45-60 cm depths of an irrigated and dryland Lethbridge SiCL, and of a Malmo CL (Appendix, Tables A1, A2 and A13). Fertilizer N was added at the rate of 100 ug/g (O.D. basis), and at the enrichment rate of approximately 10% excess of ^{15}N. The soils were incubated at the moisture level of field capacity in plastic pots which were closed, but not sealed. One replicate of samples was air-dried after 24 hours of incubation at -1°C. These will be referred to as zero-time samples. Two additional replicates were incubated for 90 days, at temperatures of -1 and +4°C. Because evaporation was not expected, no additional water was added during the incubation period. Although moisture was not measured after incubation, significant moisture loss did not occur. Samples were then air-dried, and N was analyzed by KCl extraction and steam distillation, as well as by the Kjeldahl procedure, modified to include NO_2 and NO_3-N. Collected samples of N were quantified by titration, and re-acidified samples were dried, and ^{15}N:^{14}N ratio analyses were made with a mass spectrometer.

4.3.1 Percent recovery of applied N by Kjeldahl analysis, and by KCl extraction and distillation using direct measurement and indirect (subtraction) techniques.

Recovery of applied NH_4-N by the Kjeldahl procedure was greater than by steam distillation of KCl extracts, but not complete (Table 21). Approximately 20% of applied NH_4-N was not recovered by the modified Kjeldahl procedure, and approximately 30% was not recovered by KCl extraction. These results are similar to those reported by Tomar and Soper (1981), who suggested that a portion of applied NH_4-N was rapidly retained by immobilization and/or fixation, and slowly released thereafter. After 90 days of incubation in the present study however, the extent of recovery by the Kjeldahl procedure was not greater than at zero-time.

The level of recovery of NH_4-N by KCl extraction was relatively constant for all the surface soils, but was somewhat lower from the Lethbridge irrigated subsurface soil, and markedly lower from the subsurface Malmo soil. Only 45-50% of applied NH_4-N was recovered by KCl extraction, while 80% was recovered by the Kjeldahl method.

Since the unrecovered proportion of NO_3-N was similar in size to the unrecovered portion of NH_4-N (by the modified Kjedahl procedure) it does not seem likely that the reason was NH_4-N retention by soil clay or organic matter. Rather, the accuracy of the Kjeldahl procedure in recovering a small amount of mineral N included in a relatively much larger amount of organic N should be in question. It is possible that the acid reduced iron and acid permanganate did not reduce all of the NO_3 and NO_2-N in the Kjedahl digestion.

The reason why approximately 30% of the applied NH_4-N was not recovered by KCl extraction, steam distillation and direct measurement using ^{15}N techniques is not clear. Volatile losses of ammonia from NH_4-N do not seem likely. The surface soils at Lethbridge were somewhat alkaline in reaction (Appendix, Table A1), but the Malmo Cl was not. As pointed out in Chapter 3, the fertilizer was added to the soil before it was potted and then water was added to raise the moisture level. The fertilizer was therefore well mixed throughout the soil in the pot, and not concentrated near the surface.

Table 21. Percent of applied N recovered by Kjeldahl digestion, by steam distillation and ^{15}N technique, and by steam distillation and the subtraction method.*

			% applied N recovered **		
Soil	Depth (cm)	Treatment	Kjeldahl Total ^{15}N	Distillation, ^{15}N method	Distillation, subtraction ***
Leth.	0-15	$(^{15}NH_4)_2SO_4$	77±3	75±5	72±6
dryland	45-60	"	74±3	73±8	69±1
Leth.	0-15	"	79±1	80±8	82±9
irrig.	45-60	"	89±14	70±1	69±5
Malmo	0-15	"	82±1	74±16	73±9
	45-60	"	87±2	47±4	48±7
	Mean	"	81±6	70±12	69±11
Leth.	0-15	$K^{15}NO_3$	71±8	104±5	93±7
dryland	45-60	"	76±4	108±4	99±3
Leth.	0-15	"	71±8	103±6	97±6
irrig.	45-60	"	79±11	100±4	95±3
Malmo	0-15	"	86±4	107±3	100±3
	45-60	"	82±2	106±3	99±3
	Mean	"	78±6	105±3	97±3

* values are means including the zero-time samples, and those incubated at both -1° and +4°C.

** recovered N includes NH_4 and NO_3-N for each method.

*** $\frac{\text{ug N/g (treated sample)} - \text{ug N/g (nil)}}{\text{ug N/g added}} \times 100\%$

A comparison of levels of recovery of applied NH_4-N and NO_3-N for the ^{15}N technique and the subtraction technique was made. The subtration technique is a subtraction of the nil from the treatment level. Results do not indicate that priming, or enhancement of mineralization occurred due to the addition of either NH_4-N or NO_3-N (Table 21). As reviewed by Broadbent (1965), the addition of NH_4-N can result in an increased rate of mineralization of soil N. If this had occurred, fertilizer N recovered by subtraction of the nil treatment from the respective treated samples would be higher than shown by direct measurement using ^{15}N methodology. To a limited extent, the reverse was true when NO_3-N was added (Table 21). Recovery of applied N as determined by the subtraction method was similar to that measured directly using ^{15}N methods.

Recovery of added NO_3-N by KCl extraction and ^{15}N measurement was consistently slightly higher than 100%. It is likely that the source of this error was the determination of moisture content and moisture holding capacity at 1/3 bar tension during the pre-treatment of the soils. Because this trend in consistent, recovery is interpreted by the author to be 100% (Tables 21 and 22).

Recovery of applied NO_3-N by KCl extraction and steam distillation using ^{15}N methodology was complete (Table 22). Recovery was equal regardless of soil, depth, incubation, or incubation temperature. In every soil and depth, less than 1%, or virtually none of the applied NO_3-N

Table 22. Percent recovery of applied NO_3-N at zero-time, and after incubation for 90 days at -1° and +4°C at field capacity.

		% recovery of applied N		
Soil	depth(cm)	zero-time	incubated at -1°C	incubated at +4°C
Lethbridge	0-15	102	108	100
dryland	45-60	110	108	106
Lethbridge	0-15	109	104	99
irrigated	45-60	95	103	101
Malmo	0-15	110	105	108
	45-60	103	108	106
	Mean*	105±6	106±4	103±5

* in calculation of standard deviations,
zero-time n = 6
-1°C n = 12
+4°C n = 12

was recovered as NH_4-N. The total recovery of applied NO_3-N indicates that no measured denitrification or immobilization occurred.

The levels of (NH_4+NO_3)-N in the zero-time and incubated unfertilized soils are given in the Appendix (Table A12). The changes during incubation were somewhat larger in surface soils than subsurface soils and slightly larger at +4°C incubation than -1°C.

4.3.2 Effect of incubation temperature, soil and depth on nitrification.

Incubation temperature, soil and depth of sample influenced the extent of nitrification during the incubation period (Table 23). In the surface samples of the Lethbridge irrigated and the Malmo soil, nitrification was virtually complete after incubation at +4°C for 90 days. Only 87% and 79% of the fertilizer NH_4-N was recovered in total from these soils ((NH_4+NO_3)-N), indicating that virtually all of the recovered N was in NO_3^- form. The size of the unrecovered portion of applied NH_4-N is consistent with the size of that fraction not recovered by the Kjeldahl procedure (Table 21). This suggests that approximately 15-25% of applied NH_4-N was not readily available to nitrification, nor to recovery by Kjeldahl analysis, or was lost due to volatilization.

The initial size of the nitrifying population is likely the prime factor governing nitrification in soils. Lower levels of organic matter is the probable reason for slower nitrification in the subsurface samples, than in the surface samples (Table 23).

Nitrification at -1°C was much reduced, compared to the higher incubation temperature, in all soils, but almost 30% of applied NH_4-N was recovered as NO_3-N in the irrigated surface soil. The reason for this is not clear, but perhaps the nitrifying population was higher there due to a history of higher fertilizer application rates than the dryland soil.

The data presented (Table 23) are consistent with those presented by other workers who have observed nitrification at low temperatures. They are a reminder of the potential levels of soil and fall-applied N which can be nitrified even in mid-winter months in the chinook-affected areas of southern Alberta.

Table 23. Percent recovery of applied $^{15}NH_4$-N as $^{15}NO_3$-N, measured by KCl extracted ^{15}N.

		% of applied NH_4-N recovered as NO_3-N		
Soil	depth(cm)	zero-time	incubated at -1°C	incubated at +4°C
Lethbridge	0-15	<1	8	39
dryland	45-60	<1	7	10
Lethbridge	0-15	4	61	86
irrigated	45-60	<1	5	27
Malmo	0-15	3	37	77
	45-60	<1	5	12

5. DISCUSSION OF RESULTS

The primary objective of this study was to determine if over-winter losses of soil and fertilizer N occur in the Brown, Dark Brown, and Black soil zones of southern Alberta. This question was investigated by over-winter sampling and analysis of soils, by measurement of barley yield and N uptake from fall and spring fertilizers, and by comparison of methods to slow nitrification of fall applied N. Soil moisture was raised by irrigation in fall, to see if fall-applied NO_3-N would be reduced by denitrification. Soils fertilized with ^{15}N-enriched NH_4-N and NO_3-N were incubated under conditions simulating winter or early spring in southern Alberta.

This study was initiated by the establishment of four field plots in fall, 1975. These plots were soil sampled four times between fall and spring. They included two moisture levels on adjacent stubble plots, a summerfallowed soil, and a stubble plot with both two levels of soil moisture and two levels of residual fertilizer N (Appendix, Tables A1 to 4).

The result of this preliminary study showed that levels of mineral N over winter were not static. Reductions of 10 kg N/ha in the non-irrigated stubble, and 24 kg N/ha in the stubble which was fall-irrigated occurred between January 1 and April 1. This was followed by an increase in the levels of mineral N, resulting in a net over-winter gain of 6 kg/ha and a loss of 17 kg/ha from the dry and moist stubble sites respectively, from the 0-60 cm depths (Figure 1, Table 1). Losses from the 0-120 cm depth were greater, indicating that 0-60 cm N was not merely leached into the subsurface depths. At the fall-irrigated stubble site, the NH_4-N declined continually, but it remained relatively constant in the non- irrigated plot. The decline in the level of NH_4-N was the primary factor in the decline in mineral N. These results are consistent with those reported by Read and Cameron (1979), who compared fall to spring N levels from 121 stubble site years.

Changes in the level of soil mineral N in the fallow plot at Lethbridge (Table 2, Figure 2) are also consistent with those reported by Read and Cameron (1979). An increase in the level of NO_3-N and a larger decrease in the level of NH_4-N, probably due to nitrification, over winter resulted in a net decrease in the level of mineral N over winter. The most important variable influencing the decrease was the level of N present in the fall.

Results from the preliminary stubble plot at Vauxhall suggest that soil moisture may have been a more important factor than the original level of mineral N (Table 3 and Figure 3). Mineral N to 60 cm decreased in irrigated treatments, fertilized or not. The changes in the levels of mineral N between fall and spring were smaller in the slightly drier treatments than in the more moist treatments, regardless of original levels of N. Neither moisture level exceeded field capacity, however (Appendix, Table A4). There were reductions of mineral N over winter, but analyses of the soils to include fixed, immobilized, and organic N were beyond the scope of this study. Therefore, while denitrification may be occurring at the same time as mineralization, immobilization and nitrification, the results presented do not permit resolution of this question. The reductions mentioned can only be called apparent losses.

In the major field experiment of this study, fall and spring application of N fertilizers were compared. Locations of the field plots were Vauxhall, Lethbridge and Glenwood, Alberta, to include the Brown, Dark Brown and Black soil zones, respectively. At each location, one plot site was established on dryland, and the other on soil which had been irrigated for a number of years.

Results from comparisons of fall to spring broadcast-application of N fertilizers indicate that time of application was not a significant factor at any of the sites (Tables 4, 5 and 6). At the dryland sites the response to N was severely restricted by moisture stress. Therefore, significant differences for fall versus spring in yield or N uptake response would not be expected. At irrigated sites at Lethbridge and Vauxhall, subsurface accumulations of NO_3-N and irrigation combined to produce high yields of barley. The soil NO_3-N undoubtedly reduced responses to N, but yield and N uptake responses were positive at most sites, and not different at those sites, due to time of application.

As measured by yield and N uptake, N source was not significant at the dryland sites (Tables 7, 8 and 9). The responses to urea-N were slightly lower however, than to NH_4NO_3 or $Ca(NO_3)_2$ at the dryland site at Vauxhall. This may have been related to recovery of lower levels of mineral N from fall-applied urea treatments than from NH_4NO_3 or $Ca(NO_3)_2$ at that site (Table 11a). To a depth of 30 cm at the irrigated sites at Vauxhall and Glenwood, lower recovery of fertilizer N from the fall-applied urea treatment also occurred (Table 11b). Many workers have reported the variable ability of soils to rapidly fix added NH_4-N (Kowalenko 1978; Sowden et al. 1978; Kowalenko and Ross 1980; Tomar and Soper 1981). It is likely that urea applied by broadcasting in fall was rapidly hydrolyzed (Gould 1970), and that some of of NH_4-N was fixed. The fact that low recovery of mineral N from fall applied urea was not accompanied in all cases by lower yield responses may indicate that most of the fixed NH_4-N had been released to the soil and crop during the growing season. Kowalenko (1978) reported that 59% of 152 kg N/ha was immediately fixed by an Ottawa area clay loam, and that 66% of the fixed NH_4-N was released in 86 days.

Since only NO_2- and NO_3-N are biologically denitrified by soil bacteria, effects of methods to inhibit nitrification of fall-applied urea were compared. At the dryland site at Glenwood, yield and N uptake were lower when urea was banded with or without the nitrification inhibitor ATC than when it was applied in the fall by broadcasting. This was verified by slightly lower levels of mineral N recovered from the urea and ATC banded treatment, although this difference was not significant. At the dryland sites, fall application of urea by banding reduced the extent of nitrification (Table 11a). The inclusion of the ATC in the band reduced it further. Therefore, as also reported by Malhi (1978), ATC does reduce nitrification of NH_4-N. The fact that the levels of (NH_4+NO_3)-N did not differ due to these treatments is an indication that NO_3-N formed from urea was not measurably lost from the soil.

At irrigated sites, only the use of ATC with banded urea had a significant effect on nitrification (Table 11b). It seems likely that a reduction in nitrification due to high local concentration of NH_4^+ salts (Pang et al. 1975) would be more extensive and longer-lasting in a very dry soil than in soil where soil moisture has the effect of diluting the concentrated zone.

Denitrification of soil and fertilizer N can be made to happen in most soils (Khan and Moore 1968; Bailey 1976). Malhi (1978) has shown denitrification to occur extensively in field experiments during spring thaw conditions. To a portion of each of the dryland and irrigated field plots, fall irrigation, followed by broadcast and incorporated $Ca(NO_3)_2$ was applied, to increase the possibility of the occurence denitrification. As measured by crop yield, N uptake and fall applied NO_3-N recovered in spring, there was no evidence that the higher soil moisture contents in fall resulted in denitrification of NO_3-N. It should be noted that shortly after the irrigation treatments were applied, the level of soil moisture was below field capacity, and therefore denitrification was not expected. Description of soil conditions at spring thaw by other workers (Kowalenko 1978; Malhi 1978), do not match the usual conditions in southern Alberta. Two important factors governing denitrification are restricted aeration as brought about by high soil moisture, and available carbon supply (Bremner and Shaw 1958; Alexander 1977). Both of these are characteristics by which Brown and Dark Brown soils differ from more northern or eastern Canadian soils. Lower levels of precipitation in southern Alberta and the influence of warm, drying winds (Appendix, Tables A10 and 11) significantly reduce the length of time that farm soils lie in a saturated state.

A comparison of methods of extraction of fertilizer N from soils was made using ^{15}N enriched fertilizers and incubated soils. Extraction of NO_3-N by the Kjeldahl procedure to include NO_2 and NO_3-N was incomplete, while recovery by KCl extraction was complete (Table 21). This indicated that the reduction of NO_3-N and NO_2-N by acid permanganate and reduced iron may have been incomplete, or that some of the NH_4-N was retained. Without a comparison of the two methods, incomplete Kjeldahl recovery may have been mistakenly interpreted as losses of NO_3-N.

Recovery of NH_4-N was not complete by either KCl extraction or the Kjeldahl procedure (Table 21). The Kjeldahl procedure generally extracted a little more of applied NH_4-N than did KCl extraction. This may be an indication that at least a small portion of the rapidly fixed portion of added NH_4-N is extractable by the more severe method of acid digestion, than is recoverable by KCl extraction. Kowalenko (1978) reported that over half of the rapidly fixed NH_4-N was released over 86 days, and that the remainder of the fixed portion was strongly retained over a sampling period of 17 months. Tomar and Soper (1981) suggested that retention of mineral N by soil was probably by organic immobilization after an initial, short period of inorganic fixation. The subsequent release during incubation is probably due to inorganic release followed by organic immobilization, nitrification and cation exchange reactions.

Recovery of applied NO_3-N was complete, regardless of soil, depth, incubation period or incubation temperature (Table 22). It is concluded that under the conditions of this experiment, no measurable denitrification or immobilization occurred. Gould and McCready (1981) obtained similar results. At field capacity, very little denitrification occurred. At 2 to 4 times field capacity, only limited denitrification occured in Brown and Dark Brown soils, unless available carbon was added. Mahli (1978) reported measurable denitrification in one of the soils used in the present study (Malmo SiCL). Denitrification was measured at -4°C and flooded moisture condition, and at -15 bar moisture tension and 20°C. His work indicates the interdependance of at least two factors which are necessary for denitrification to occur. Either restriction of aeration or suitable temperature requirements must be met. Apparently, the combinations of these two factors which were used in the present study did not favor denitrification.

The recovery of applied $^{15}NH_4$-N as $^{15}NO_3$-N serves as a direct measurement of the extent of nitrification. Results of the present study indicate that nitrification occurred at -1°C, and to a much greater extent at +4°C. These results support those of other workers who have reported rapid nitrification, even at low temperatures. They are also an indication of the ability of soils in southern Alberta to nitrify both mineralized soil N and fall-applied fertilizer N under conditions which are quite representative of over-winter conditions in southern Alberta.

In conclusion, although nitrification was shown to be extensive in both field and incubation experiments, no evidence specifically pointing to either denitrification or immobilization was discovered. This is the primary difference between results of the present study, and results of similarly performed experiments in more northern regions (Mahli 1978). This difference is attributed by the author, to soil factors which are different in southern Alberta from those in more northern regions. They are soil organic matter (at least in the Chernozemic soils), and soil moisture (as it affects aeration). The primary factors stated above also have a bearing on microbial populations and substrate supply. Other factors involved are temperature, and cost importantly, the length of time all of the above factors combine in such a way that significant losses of N are likely to occur. As with any other biological reaction in soil, one cannot say that denitrification does not occur, but results of the present study provided little evidence that it does.

6. CONCLUSIONS

In this study, several approaches have been used to investigate over-winter changes in the levels of soil mineral N, the efficacy of fall application of N, and the occurrence and extent of losses of N from the soil. Using measurements including yields, N uptake by the crop, spring measurements of fall-applied N and recovery of labelled fertilizers from incubated soils, the following conclusions were reached:

1. Apparent net decreases in the level of soil mineral N occurred over winter. Mineralization and nitrification occurred, but the decreases in the level of soil mineral N in the field could not be attributed to either denitrification or immobilization.

2. Some evidence was presented that soils fix a portion of added NH_4-N quickly, and that fixing capacity varies with depth.

3. Results from six field experiments and an N-15-labelled soil incubation experiment showed no evidence of denitrification or immobilization. Although recovery of fall-applied N was not complete, higher soil moisture from a 10 cm fall irrigation was not sufficient to affect the recovery of fall applied NO_3-N in spring. Crop uptake of N was not reduced by fall rather than spring application.

7. REFERENCES

Agarwal, A. S., Singh, B. R. and Y. Kanehiro. 1971. Ionic effect of salts on mineral nitrogen release in an allophanic soil. Soil Sci. Soc. Am. Proc. 35: 454-457.

Alexander, M. 1961. Mineralization and immobilization of nitrogen. pp. 248-271. In Introduction to Soil Microbiology. John Wiley and Sons Inc., New York.

Alexander, M. 1965. Nitrification. pp. 307-343. In W.V. Bartholomew and F.E. Clark, eds. Soil Nitrogen Monograph No. 10, Am. Soc. Agron. Madison, Wisconsin.

Alexander, M. 1977. Denitrification. pp. 272-286. In Introduction to Soil Microbiology ed. 2. John Wiley and Sons Inc., Toronto.

Allison, F. E. 1955. The enigma of soil nitrogen balance sheets. Adv. Agron. 7: 213-250.

Allison, F. E. 1965. Organic carbon Walkley-Black method. pp. 1372-1376 In C.A. Black, ed. Monograph No. 9, Am. Soc. Agron. Madison, Wisconsin.

Allison, F. E., Carter, J. H. and L. D. Stirling. 1960. The effect of partial pressure of oxygen on denitrification in soil. Soil Sci. Soc. Am. Proc. 24: 283-285.

Anderson, O. E. and E. R. Purvis. 1955. Effects of low temperatures on nitrification of ammonia in soils. Soil Sci. 80: 313-318.

Anderson, O. E. and F. C. Boswell. 1964. The influence of low temperature and various concentrations of ammonium nitrate on nitrification in acid soils. Soil Sci. Soc. Am. Proc. 28: 525-529.

Bailey, L. D. 1976. Effects of temperature and root on denitrification in a soil. Can. J. Soil Sci. 56: 79-87.

Bailey, L. D. and E. D. Beauchamp. 1973. Effects of temperature on NO_3^- and NO_2^- reduction, nitrogenous gas production, and redox potential in a saturated soil. Can. J. Soil Sci. 53: 213-218.

Boswell, F. C. 1971. Comparison of fall, winter or spring N-P-K fertilizer applications for corn and cotton. Agron. J. 63: 905-907.

Boswell, F. C., Futral, J. G. and O. E. Anderson. 1974. Comparison of fall-applied N under formed beds with conventional spring N application for corn production. Agron. J. 66: 374-377.

Bouyoucos, G. B. 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54: 464-465.

Bowman, R. A. and D. D. Focht. 1974. The influence of glucose and nitrate concentration upon denitrification rates in sandy soils. Soil Biol. Biochem. 6: 297-301.

Bremner, J. M. and K. Shaw. 1958. Denitrification in soil: II. Factors affecting denitrification. J. Agr. Sci. 51: 40-52.

Bremner, J. M. 1960. Determination of nitrogen in soil by the Kjeldahl method. J. Agr. Sci. 55: 1-23.

Bremner, J. M. and D. R. Keeney. 1966. Determination and isotope ratio analysis of different forms of nitrogen in soils : 3. Exchangeable ammonium, nitrite and nitrate by extraction-distillation methods. Soil Sci. Soc. Am. Proc. 30: 577-582.

Bremner, J. M. and L. G. Bundy. 1974. Inhibition of nitrification in soils by volatile sulphur compounds. Soil Biol. Biochem. 6: 161-165.

Bremner, J. M. and M. I. Zantua. 1975. Enzyme activity in soils at subzero temperatures. Soil Biol. Biochem. 7: 383-387.

Broadbent, F. E. 1965. Effect of fertilizer nitrogen on the release of soil nitrogen. Soil Sci. Soc. Am. Proc. 29: 692-696.

Broadbent, F. E. and F. Clark. 1965. pp. 347-362. In W. V. Bartholomew and F. E. Clark, eds. Soil Nitrogen. Monograph no. 10. Am. Soc. Agron. Madison, Wisconsin.

Broadbent, F. E. and T. Nakashima. 1971. Effect of added salts on nitrogen mineralization in three California soils. Soil Sci. Soc. Am. Proc. 35: 457-460.

Bundy, L. G. and J. M. Bremner. 1973. Inhibition of nitrification in soils. Soil Sci. Soc. Am. Proc. 37: 396-398.

Bundy, L. G. and J. M. Bremner. 1974. Effects of nitrification inhibitors on transformations of urea nitrogen in soils. Soil Biol. Biochem. 6: 369-376.

Burford, J. R. and J. M. Bremner. 1975. Relationships between the denitrification capacities of soils and total, water-soluble and readily decomposable soil organic matter. Soil Biol. Biochem. 7:389-394.

Campbell, C. A., Ferguson, W. S. and F. G. Warder. 1970. Winter changes in soil nitrate and exchangeable ammonium. Can. J. Soil Sci. 50: 151-162.

Campbell, C. A., Biederbeck, V. O. and F. G. Warder. 1970. Simulated early spring thaw conditions injurious to soil microflora. Can. J. Soil Sci. 50: 257-259.

Chalk, R. M., Keeney, D. R. and L. M. Walsh. 1975. Crop recovery and nitrification of fall and spring applied anhydrous ammonia. Agron. J. 67: 37-41.

Clark, F. E. 1967. Bacteria in soil. pp. 15-49. In A. Burges and F. Raw, eds. Soil biology. Academic Press, New York.

Dancer, W. S., Peterson, L. S. and G. Chesters. 1973. Ammonification and nitrification of N as influenced by soil pH and previous N treatments. Soil Sci. Soc. Am. Proc. 37: 67-69.

Devine, J. E. and M. R. J. Holmes. 1964. Field experiments comparing autumn and spring applications of ammonium sulphate, ammonium nitrate, and calcium nitrate for winter wheat. J. Agr. Sci. 63: 69-74.

Dubey, H. D. 1968. Effect of soil moisture levels on nitrification. Can. J. Microbiol. 14: 1,348-1,350.

Fisher, W. B. and W. L. Parks. 1958. Influence of soil temperature on urea hydrolysis and subsequent nitrification. Soil Sci. Soc. Am. Proc. 22: 247-248.

Frederick, L. R. 1956. The formation of nitrate from ammonium nitrogen in soils. I. Effect of temperature. Soil Sci. Soc. Am. Proc. 20: 496-500.

Frederick, L. R. 1957. Formation of nitrate from ammonium nitrogen in soils. II. Effect of population of nitrifiers. Soil Sci. 83: 481-485.

Frye, W. W. 1977. Fall vs spring sulphur-coated urea, uncoated urea and sodium nitrate for corn. Agron. J. 69: 278-282.

Gardner, W. R. 1965. Movement of nitrogen in soil. pp. 550-572. In W.V. Bartholomew and F. E. Clark, Eds. Soil nitrogen. Monograph No. 10. Am. Soc. Agron. Madison, Wisconsin.

Greenwood, D. J. 1961. The effect of oxygen concentration on the decomposition of organic materials in soil. Plant Soil 14: 360-376.

Gould, W. D. 1970. Urea hydrolysis in soil. M.Sc. Thesis. University of Alberta, Edmonton, Alberta.

Gould, W. D. and R. G. L. McCready. 1981. Denitrification in several Alberta soils: Inhibition by oxidized sulphur intermediates. Unpublished paper. Agriculture Canada Research Station, Lethbridge, Alberta.

Gurovich, E. and Y. Avnimelech. 1977. The distribution of ammonium ion from a localized source into the soil. Plant Soil 46: 101-111.

Harapiak, J. T. 1979a. Alberta situation - comparison of fall and spring applied nitrogen. pp. 37-43. In Effective use of nutrient resources in crop production. Proceedings of the Alberta Soil Science Workshop, Lethbridge, Alberta.

Harapiak, J. T. 1979b. A case for sub-surface banding of fertilizer. pp. 85-98. In Effective use of nutrient resources in crop production. Proceedings at the Alberta Soil Science Workshop, Lethbridge, Alberta.

Harmsen, G. W. and D. A. Van Schreven. 1955. Mineralization of organic nitrogen in soil. Adv. Agron. 7: 299-398.

Harmsen, G. W. and G. J. Kolinbrander. 1965. Soil inorganic nitrogen. pp. 43-92. In W.V. Bartholomew and F.E. Clark, Eds. Soil nitrogen. Monograph No. 10 Am. Soc. Agron. Madison, Wisconsin.

Hogg, T. J., Halstead, E. H. and E. A. Paul. 1977. Studies on the effectiveness of the nitrification inhibitor ATC. University of Saskatoon 12th Annual Report. Saskatoon, Saskatchewan.

Huber, D. M., Murray, G. A. and J. M. Crane. 1969. Inhibition of nitrification as a deterrent to nitrogen loss. Soil Sci. Soc. Am. Proc. 33: 975-976.

Huber, D. M., Warren, N. L., Nelson, D. W. and C. Y. Tsai. 1977. Nitrification inhibitors - new tools for food production. Bio. Science 27: 523-529.

Jansson, S. L. and F. E. Clark. 1952. Losses of nitrogen during decomposition of plant material in the presence of inorganic nitrogen. Soil Sci. Soc. Am. Proc. 16: 300-334.

Jones, R. W. and R. A. Hedlin. 1970. Ammonium, nitrite and nitrate accumulation in three Manitoba soils as influenced by added ammonium sulfate and urea. Can. J. Soil Sci. 50: 331-338.

Justice, J. K. and R. L. Smith. 1962. Nitrification of ammonium sulphate in a calcareous soil as influenced by combinations of moisture, temperature, and levels of added nitrogen. Soil. Sci. Soc. Am. Proc. 26: 246-250.

Khan, M. F. A. and A. W. Moore. 1968. Denitrifying capacity of some Alberta soils. Can. J. Soil Sci. 48: 89-91.

Kowalenko, C. G. and D. R. Cameron. 1976. Nitrogen transformations in an incubated soil as affected by combinations of moisture content and temperature and adsorption-fixation of ammonium. Can. J. Soil Sci. 56: 63-70.

Kowalenko, C. G. 1978. Nitrogen transformations and transport over 17 months in field fallow microplots using ^{15}N. Can. J. Soil Sci. 58: 69-76.

Kowalenko, C. G. and G. J. Ross. 1980. Studies on the dynamics of "recently" clay-fixed NH_4^+ using ^{15}N. Can. J. Soil Sci. 60: 61-70.

Ladd, J. N., Parsons, J. W. and M. Amato. 1977. Studies of nitrogen immobilization and mineralization in calcareous soils. II. Mineralization of immobilized nitrogen from soil fractions of different particle size and density. Soil Biol. Biochem. 9: 319-325.

Larsen, J. E. and H. Kohnke. 1946. Relative merits of fall and spring applied nitrogen fertilizer. Soil Sci. Soc. Am. Proc. 11: 378-383.

Laura, R. O. 1976. Effects of alkali salts on carbon and nitrogen mineralization of organic matter in soils. Plant Soil 44: 587-596.

Lees, H. 1946. Effect of copper-enzyme poisons on soil nitrification. Nature 158: 97-99.

Lees, H. and J. H. Quastel. 1946. The site of soil nitrification. Biochem. J. 40: 815-823.

Leitch, R. H. 1973. Comparison of uptake of applied ammonium and nitrate nitrogen by crops. M.Sc. Thesis, University of Alberta, Edmonton, Alberta.

Leitch, R. H. and M. Nyborg. 1972. A comparison of ammonium and nitrate in N fertilizers. In Proceedings of the Soil Science Workshop, Department of Soil Science, University of Alberta, Edmonton, Alberta.

Mahendrappa, M. K., Smith, R. L. and A. T. Christiansen. 1966. Nitrifying organisms affected by climatic region in western United States. Soil Sci. Soc. Am. Proc. 30: 60-62.

Malhi, S. S. and M. Nyborg. 1974. A preliminary report on the comparison of fall and spring application of fertilizer N. In Proceedings of the Alberta Soil Science Workshop, University of Alberta, Edmonton, Alberta.

Malhi, S. S. 1978. Over-winter losses of mineral nitrogen. Ph.D. Thesis, University of Alberta, Edmonton, Alberta.

Meints, V. W. and G. A. Peterson. 1972. Further evidence for the inability of the Kjeldahl total nitrogen method to fully measure indigenous fixed ammonium nitrogen in subsoils. Soil Sci. Soc. Am. Proc. 36: 434-436.

Miller, H. F., Kavanaugh, J. and G. W. Thomas. 1975. Time of N application and yields of corn in alluvial soils. Agron. J. 67: 401-404.

Myers, R. J. K. and J. W. McGarity. 1971. Factors influencing high denitrifying activity in the subsoil of a solodized solonetz. Plant Soil 35: 145-160.

McAllister, R. E. 1969. A summary of field experiments on fall and spring application of N fertilizers. Mimeographed Report. Cominco Ltd., Calgary, Alberta.

McGarity, J. W. 1961. Denitrification studies on some south Australian soils. Plant Soil 14: 1-21.

McGill, W. B. and K. Hruday. 1981. Mass spectrometer operating procedure. Personal communication. Department of Soil Science, University of Alberta, Edmonton, Alberta.

McIntosh, T. H. and L. R. Frederick. 1958. Distribution and nitrification of anhydrous ammonia in a Nicollet sandy clay loam. Soil Sci. Soc. Am. Proc. 22: 402-405.

McKenzie, E. Jr. and L. T. Kurtz. 1976. Effect of pretreatment on loss of nitrogen-15-labelled fertilizer nitrogen from waterlogged soil during incubation. Soil Sci. Soc. Am. J. 40: 534-537.

McLaren, A. D. 1971. Kinetics of nitrification in soil: Growth of nitrifiers. Soil Sci. Soc. Am. Proc. 35: 91-95.

Nommik, H. 1956. Investigations on denitrification. Acta Agric. Scand. 6: 195-228.

Olson, R. A., Dreier, A. F., Thompson, C. and P. H. Grabouski. 1964. Using fertilizer nitrogen effectively on grain crops. Nebraska Agr. Exp. Sta. Res. Bull. SB - 479.

Owens, L. D. 1960. Nitrogen movement and transformations in soil as evaluated by a lysimeter study utilizing isotopic nitrogen. Soil Sci. Soc. Am. Proc. 24: 372-376.

Pang, P. C., Cho, C. M. and R. A. Hedlin. 1975a. Effects of nitrogen concentration on the transformation of band-applied nitrogen fertilizers. Can. J. Soil Sci. 55: 23-27.

Pang, P. C., Cho, C. M. and R. A. Hedlin. 1975b. Effects of pH and nitrifier population on nitrification of band-applied and homogeneously mixed urea nitrogen in soils. Can. J. Soil Sci. 55: 15-21.

Parnas, H. 1976. A theoretical explanation of the priming effect based on microbial growth with two limiting substrates. Soil Biol. Biochem. 8: 139-144.

Paul, E.A. and R.L. Victoria. 1978. N transfers between soil and atmosphere. Chapter 41, pp. 541-555. In W.E. Krumbeine, ed. Environmental biogeochemistry and geomicrobiology, Vol. 2. The terrestrial environment. Ann Arbor Science Publications Inc. Ann Arbor, Michigan.

Partridge, J. R. D. and A. O. Ridley. 1974. Effect of nitrogen fertilizer applied in spring or fall on yields of barley. Manitoba Agronomists Conference. University of Manitoba, Winnipeg, Manitoba.

Passioura, J. B. and R. Wetselaar. 1972. Consequences of banding nitrogen fertilizers in soil. II. Effects on the growth of wheat roots. Plant Soil 36: 461-473.

Porter, L. K. and W. A. O'Deen. 1977. An apparatus for preparing nitrogen from ammonium chloride for nitrogen-15 determination. Anal. Chem. 49: 514-516.

Powlson, D. S. and D. S. Jenkinson. 1971. Inhibition of nitrification in soil by CS_2 from rubber bungs (soil fumigation). Soil Biol. Biochem. 3: 267-269.

Prasad, R., Rajale, G. B. and B. A. Lakhdive. 1971. Nitrification retarders and slow-release nitrogen fertilizers. Adv. Agron. 23: 337-383.

Pratt, P. F., Cannel, G. H., Garber, M. J. and F. L. Bair. 1967. The effect of three nitrogen fertilizers on gains, losses, and distribution of various elements in irrigated lysimeters. Hilgardia 38: 265-283.

Read, D. W. L. and D. R. Cameron. 1979. Changes in the amount of nitrogen and phosphorus in the soil between fall and spring sampling. Can. J. Soil Sci. 59: 271-276.

Reddy, K. R., and W. H. Patrick. Jr. 1975. Effect of alternate aerobic and anaerobic conditions on redox potential, organic matter decomposition and nitrogen loss in a flooded soil. Soil Biol. Biochem. 7: 87-94.

Rennie, D. A., Paul, E. A. and L. E. Johns. 1976. Natural nitrogen-15 abundance of soil and plant samples. Can. J. Soil Sci. 56: 43-50.

Russel, J. C., Jones, E. G. and G. M. Bahrt. 1925. The temperature and moisture factors in nitrate production. Soil Sci. 19: 381-398.

Sabey, B. R., Frederick, L. R. and W. V. Bartholomew. 1959. The formation of nitrate from ammonium in soils: III. Influence of temperature and initial population of nitrifying organisms on the maximum rate and delay period. Soil Sci. Soc. Am. Proc. 23: 462-465.

Smid, A. E., and E. G. Beauchamp. 1976. Effects of temperature and organic matter on denitrification in soil. Can. J. Soil Sci. 56: 385-391.

Sowden, F. J. 1976. Transformation of nitrogen added as ammonium and manure to soil with a high ammonium-fixing capacity under laboratory conditions. Can. J. Soil Sci. 56: 319-331.

Sowden, F. J., McLean, A. A. and G. J. Ross. 1978. Native clay- fixed ammonium content, and the fixation of added ammonium of some soils of Eastern Canada. Can. J. Soil Sci. 58: 27-38.

Spratt, E. D. 1974. Effect of ammonium and nitrate forms of fertilizer N and their time of application on utilization of N by wheat. Agron. J. 66: 57-61.

Spratt, E. D. and J. K. R. Gasser. 1970. Effect of ammonium and nitrate forms of nitrogen and restricted water supply on growth and nitrogen uptake of wheat. Can. J. Soil Sci. 50: 263-273.

Stanford, G., Dziena, S. and R. A. Vander Pol. 1975. Effect of temperature on denitrification rate in soils. Soil Sci. Soc. Am. Proc. 39: 867-870.

Stanford, G., Vander Pol, R. A. and S. Dziena. 1975. Denitrification rates in relation to total and extractable soil carbon. Soil Sci. Soc. Am. Proc. 39: 284-289.

Steel, R. G. D. and J. H. Torrie. 1960. Principles and procedures of statistics. McGraw Hill Book Co. Ltd., New York.

Stephanson, K. C. 1976. Denitrification from nitrogen fertilizer placed at various depths in the plant-soil system. Soil Sci. 121: 353-363.

Stojanovich, D. Y. and M. Alexander. 1958. Effect of inorganic N on nitrification. Soil Sci. 86: 208-215.

Tomar, J. S. and R. J. Soper. 1981. An incubation study of nitrogen added as urea to several Manitoba soils with particular reference to retention of nitrogen. Can. J. Soil Sci. 61:1-10.

Van Cleemput, O. and W. H. Patrick. Jr. 1974. Nitrate and nitrite reduction in flooded gamma-irrigated soil under controlled pH and redox potential conditions. Soil Biol. Biochem. 6: 85-88.

Viets, F. G. 1965. The plant's need for and use of nitrogen. pp. 508-554. In W.V. Bartholomew and F.E. Clark, Eds. Soil nitrogen. Monograph no. 10. Am. Soc. Agron. Madison, Wisconsin.

Wagner, G. H. and G. F. Smith. 1958. Nitrogen losses from soils fertilized with different nitrogen carriers. Soil Sci. 85: 125-129.

Waksman, S. A. and M. R. Madhok. 1937. Influence of light and heat on formation of nitrates in soil. Soil Sci. 44: 361-375.

Wetselaar, R. 1961. Nitrate distribution in tropical soils. II. Extent of capillary accumulation of nitrate during a long dry period. Plant Soil 15: 121-133.

Wetselaar, R. 1962. Nitrate distribution in tropical soils. III. Downward movement and accumulation of nitrate in the subsoil. Plant Soil 16: 19-31.

Wetselaar, R., Passioura, J. B. and B. R. Singh. 1972. Consequences of banding nitrogen fertilizers in soil. I. Effects on nitrification. Plant Soil 36: 159-175.

Widdowson, F. V., Penny, A. and R. J. B. Williams. 1961. Autumn nitrogen for winter wheat. J. Agr. Sci. 57: 329-332.

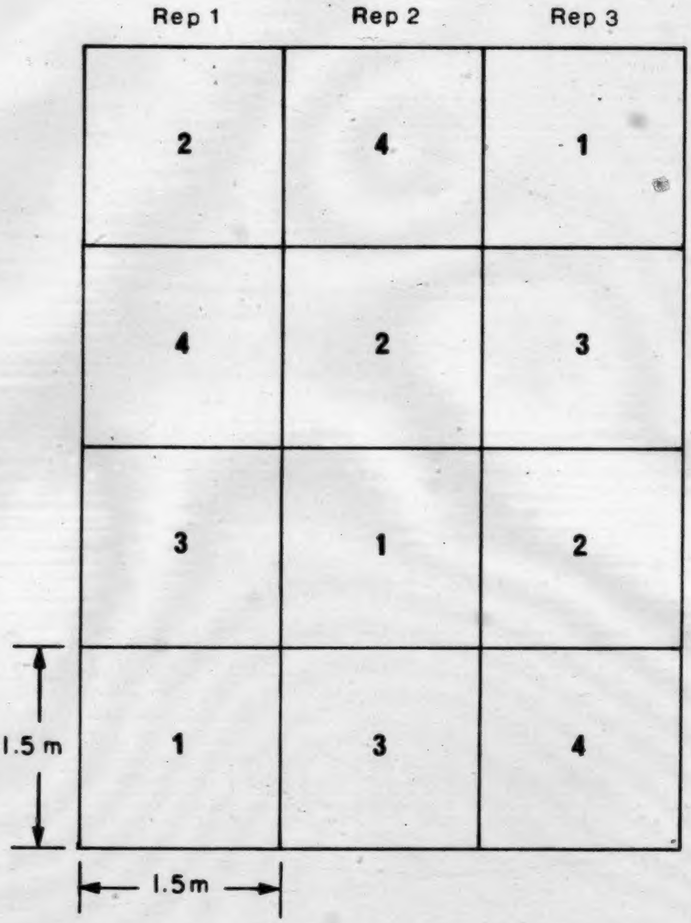
Wijler, J. and C. C. Delwiche. 1954. Investigations on the denitrification process in soil. Plant Soil 5: 155-169.

Wildung, R. E., Garland, J. R. and R. L. Buschbom. 1975. The interdependant effects of soil temperature and water content on soil respiration rate and plant root decomposition in arid grassland soils. Soil Biol. Biochem. 7: 373-378.

Woldendorp, J. W. 1962. The quantitative influence of the rhizosphere on denitrification. Plant Soil 17: 267-270.

Yimprasert, S., Blevins, R. L. and S. Chaewsamoot. 1976. The movement of nitrate, chloride and potassium in a sandy loam soil. Plant Soil 45: 227-234.

8. APPENDIX

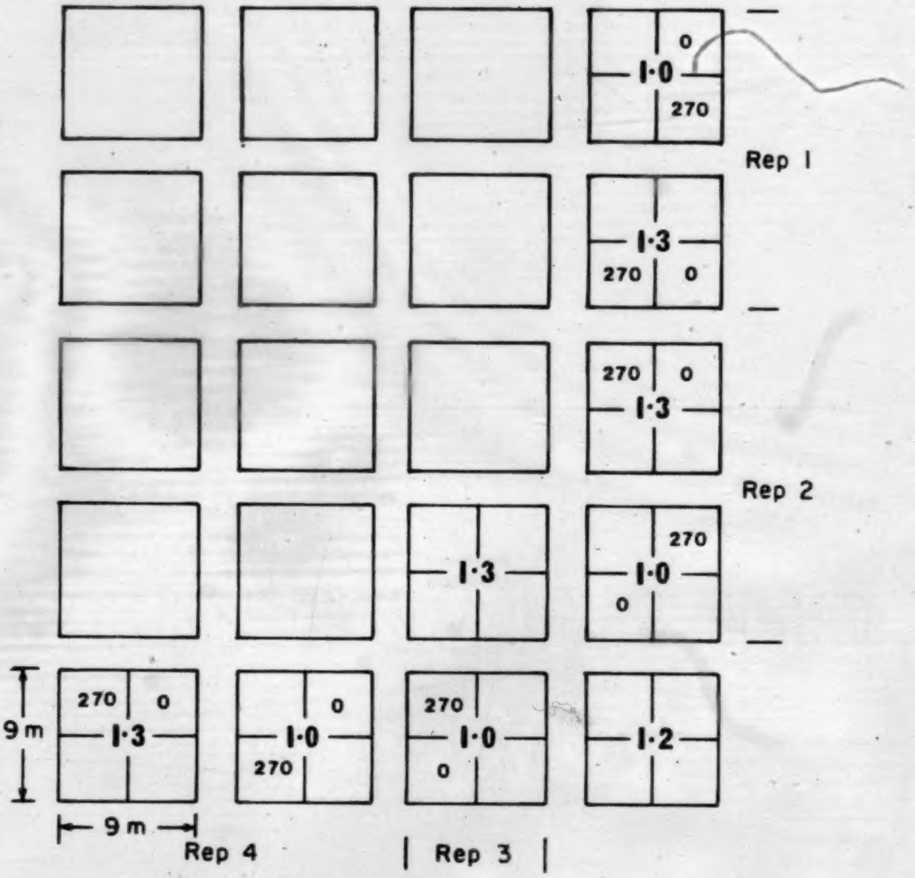


Rep 1	Rep 2	Rep 3
2	4	1
4	2	3
3	1	2
1	3	4

Dates of Sampling

1. December 28, 1975
2. February 24, 1976
3. April 2, 1976
4. April 28, 1976

Figure A1. Field plan and dates of sampling of preliminary stubble and summerfallow plots at Lethbridge, 1976.



Treatments sampled

1.0 - no irrigation throughout 1975 growing season
1.3 - irrigated throughout 1975 growing season
0 - no N applied in the spring of 1975
270 - 270 kg N/ha applied as NH_4NO_3 in the spring of 1975

Sampling dates

December 28, 1975
February 24, 1976
April 2, 1976
April 28, 1976

Figure A2. Field plan, list of previously applied treatments which were sampled, and sampling dates of preliminary stubble plot at Vauxhall, 1975-76.

BORDER			
Rep. 1 - 9	Rep. 2 - 11	Rep. 3 - 9	Rep. 4 - 5
2	4	2	10
1	5	11	3
10	6	4	9
3	1	5	6
BORDER			
8	7	8	7
7	8	7	8
BORDER			
5	2	1	11
11	9	6	2
4	3	10	1
6	10	3	4
BORDER			

treatment size: 1.8 x 1.6 m

List of treatments

1. Control
2. Urea broadcast* - fall
3. Ammonium nitrate broadcast - fall
4. Calcium nitrate broadcast - fall
5. Urea banded - fall
6. Urea + 2% ATC banded - fall
7. Fall irrigated control
8. Fall irrigated plus calcium nitrate broadcast - fall
9. Urea broadcast - spring
10. Ammonium nitrate broadcast - spring
11. Calcium nitrate broadcast - spring

*fertilizers applied by broadcasting were immediately incorporated to a 10 cm depth with a roto-tiller.

Figure A3. Field plan and list of treatments used in the main field experiment.

Table A1. Description of soils used in field and incubation studies.

Site	Depth (cm)	Textural class	pH	EC (mmhos/ cm^2)	SAR	%OM	%N
Preliminary	0-15	CL	7.9	.82	.2	2.03	.16
Lethbridge	15-30	CL	7.7	.55	.2	1.36	.10
non-irrigated	30-60	CL	7.9	.44	.3	.79	.06
stubble	60-90	SCL	8.2	.44	.3	.48	.04
	90-120	CL	8.2	2.13	.5	.43	.04
Preliminary	0-15	CL	7.7	.89	.2	2.17	.17
Lethbridge	15-30	CL	7.9	.55	.2	1.45	.07
fall-irrigated	30-60	CL	8.0	.44	.3	.83	.07
stubble	60-90	CL-SCL	8.1	.48	.3	.53	.04
	90-120	CL	7.7	4.27	.4	.55	.03
Preliminary	0-15	L	7.7	.74	.2	1.84	.14
Lethbridge	15-30	CL	7.6	.65	.2	1.84	.14
fallow	30-60	CL	7.7	.44	.3	1.16	.09
	60-90	L-CL	8.0	.45	.3	.59	.04
	90-120	CL	8.3	.51	.5	.34	.03
Preliminary	0-15	SL	7.2	.98	1.2	1.36	.09
Vauxhall	15-30	SL-L	7.6	2.18	3.8	.93	.07
corn	30-60	L	7.6	5.42	6.6	.79	.05
stubble	60-90	SCL	7.8	7.59	10.6	.47	.04
	90-120	SCL	8.0	9.71	14.7	.34	.04
Main field experiment sites							
Vauxhall	0-15	SL	7.4	1.10	1.6	2.10	.14
dryland	15-30	L	7.5	2.35	5.2	1.05	.09
	30-60	CL	7.8	7.33	9.6	.81	.08
	60-90	L-CL	8.0	9.49	13.4	.45	.05
	90-120	SCL	8.1	11.29	16.5	.57	.04
Vauxhall	0-15	L-SL	7.0	.77	2.0	1.57	.12
irrigated	15-30	L	7.7	1.30	3.6	.88	.08
	30-60	CL	7.7	3.66	3.6	.59	.06
	60-90	CL	8.0	3.37	6.5	.41	.04
	90-120	CL	7.8	5.80	7.6	.53	.04
Lethbridge	0-15	L-CL	7.6	.51	.3	1.91	.15
dryland	15-30	CL	7.8	.44	.3	1.24	.11
	30-60	CL	7.9	.56	.4	.90	.09
	60-90	CL	7.9	.56	.3	.67	.06
	90-120	CL	7.8	3.37	1.6	.74	.05
Lethbridge	0-15	CL	7.8	.65	.6	2.60	.18
irrigated	15-30	CL	7.8	.58	.7	1.76	.12
	30-60	CL	7.7	1.27	.9	1.12	.10
	60-90	C	7.7	3.48	1.2	.76	.08
	90-120	CL	7.8	3.37	1.6	.74	.05

Table A1 (continued).

Site	Depth (cm)	Textural class	pH	EC (mmhos/ cm^2)	SAR	%OM	%N
Glenwood	0-15	C	6.1	.55	.2	4.52	.28
dryland	15-30	HC	7.1	.83	.2	2.31	.15
	30-60	HC	7.6	.52	.3	1.59	.13
	60-90	HC	8.1	.44	.8	.88	.08
	90-120	HC	8.3	.60	2.4	.71	.05
Glenwood	0-15	C	7.7	.74	.2	2.98	.15
irrigated	15-30	C	7.8	.55	.2	1.24	.11
	30-60	CL	8.1	.52	.4	.83	.07
	60-90	C	8.3	.98	1.4	.47	.04
	90-120	C	8.0	4.31	1.1	.28	.03
Incubation study soils							
Lethbridge	0-15	L-CL	7.2	.65	.2	1.77	.13
dryland	45-60	CL	7.6	.47	.3	1.23	.11
Lethbridge	0-15	CL	7.8	.97	.5	2.60	.18
irrigated	45-60	CL	7.7	.60	.6	1.14	.11
Malmo	0-15	C	6.4	.60	.3	8.20	.48
	45-60	CL-C	6.8	.42	.5	3.94	.25

* pH - water saturated paste

Table A2. Mechanical analysis of soils used in field and incubation studies.

Soil	depth(cm)	% Sand	% Silt	% Clay	Textural Class
Lethbridge non-irrigated stubble	0-15	39	29	32	CL
	15-30	37	28	35	CL
	30-60	38	29	33	CL
	60-90	47	25	28	SCL
	90-120	35	29	36	CL
Lethbridge fall-irrigated stubble	0-15	35	33	32	CL
	15-30	34	31	35	CL
	30-60	39	30	31	CL
	60-90	44	28	28	CL-SCL
	90-120	33	30	37	CL
Lethbridge fallow	0-15	40	31	29	L
	15-30	33	34	32	CL
	30-60	29	36	35	CL
	60-90	46	27	27	L-CL
	90-120	40	29	31	CL
Vauxhall stubble	0-15	58	25	17	SL
	15-30	52	30	18	SL-L
	30-60	44	31	25	L
	60-90	52	26	22	SCL
	90-120	51	24	25	SCL
Main field experiments					
Vauxhall dryland	0-15	53	30	17	SL
	15-30	44	31	25	L
	30-60	36	34	30	CL
	60-90	45	29	26	L-CL
	90-120	46	24	30	SCL
Vauxhall irrigated	0-15	53	29	18	L-SL
	15-30	43	30	27	L
	30-60	38	31	31	CL
	60-90	38	31	31	CL
	90-120	37	32	31	CL
Lethbridge dryland	0-15	41	32	27	L-CL
	15-30	40	28	32	CL
	30-60	36	27	37	CL
	60-90	37	29	34	CL
	90-120	43	25	33	CL

Table A2 (continued).

Soil	depth(cm)	% Sand	% Silt	% Clay	Textural Class
Lethbridge irrigated	0-15	32	30	38	CL
	15-30	34	30	36	CL
	30-60	22	40	38	CL
	60-90	27	33	40	C
	90-120	33	29	38	CL
Glenwood dryland	0-15	19	26	55	C
	15-30	12	25	63	HC
	30-60	15	23	62	HC
	60-90	13	22	65	HC
	90-120	11	22	67	HC
Glenwood irrigated	0-15	24	34	42	C
	15-30	21	34	45	C
	30-60	21	40	39	CL
	60-90	18	39	43	C
	90-120	18	39	43	C
^{15}N incubated soils					
Lethbridge dryland	0-15	43	29	28	L-CL
	45-60	36	34	30	CL
Lethbridge irrigated	0-15	36	30	34	CL
	45-60	38	28	34	CL
Malmo	0-15	21	38	41	C
	45-60	22	38	40	CL-C

Table A3. Levels of NH_4-N and NO_3-N in soils used in preliminary field experiments at Lethbridge and Vauxhall in December, 1975.

Plot	Depth (cm)	kg N/ha		
		NH_4-N	NO_3-N	Total
Lethbridge non-irrigated stubble	0-15	4	11	15
	15-30	4	6	10
	30-60	9	9	18
	60-90	10	6	16
	90-120	22	13	35
	Total	49	45	94
Lethbridge fall-irrigated stubble	0-15	6	13	19
	15-30	9	10	19
	30-60	12	12	24
	60-90	15	18	33
	90-120	17	7	24
	Total	59	60	119
Lethbridge fallow	0-15	12	25	37
	15-30	16	28	44
	30-60	21	24	45
	60-90	20	9	29
	90-120	22	8	30
	Total	91	94	185
Vauxhall stubble a. non-irrigated N-0	0-15	6	11	17
	15-30	6	7	13
	30-60	12	48	60
	60-90	13	61	74
	90-120	16	39	55
	Total	53	166	219
b. irrigated N-0	0-15	16	8	24
	15-30	8	7	15
	30-60	18	55	73
	60-90	21	50	71
	90-120	23	70	93
	Total	86	190	276
c. non-irrigated N-270	0-15	24	93	117
	15-30	10	48	58
	30-60	16	67	83
	60-90	13	90	103
	90-120	16	46	62
	Total	79	344	423
d. irrigated N-270	0-15	10	18	28
	15-30	9	21	30
	30-60	15	89	104
	60-90	21	84	105
	90-120	29	65	94
	Total	84	277	361

Table A4. Soil moisture (%, O.D. basis) of preliminary stubble and summerfallow plots at Lethbridge and Vauxhall, 1975-1976.

		Sampling Date			
Plot	Depth (cm)	December 28/75	February 24/76	April 02/76	April 28/76
Lethbridge	0-15	20.8	17.6	16.5	19.9
non-irrigated	15-30	22.4	27.2	17.0	17.9
stubble	30-60	10.5	13.1	12.3	13.3
	60-90	9.4	8.4	9.0	9.0
	90-120	16.3	15.6	14.4	15.5
Lethbridge	0-15	28.9	21.6	21.9	21.5
fall-irrigated	15-30	25.1	24.8	21.0	21.2
stubble	30-60	16.3	15.2	16.2	17.6
	60-90	13.7	12.4	11.4	14.1
	90-120	15.6	22.2	17.1	20.0
Lethbridge	0-15	17.8	16.0	17.9	20.2
summerfallow	15-30	25.3	30.1	18.8	21.2
	30-60	18.5	19.7	18.9	20.5
	60-90	15.3	13.9	13.5	15.4
	90-120	12.8	12.2	12.2	12.6
Vauxhall	0-15	14.3	10.3	10.8	13.2
non-irrigated	15-30	10.3	11.1	10.1	11.4
treatments	30-60	13.1	18.8	11.4	12.2
	60-90	12.9	14.3	12.8	12.2
	90-120	14.0	14.9	12.8	14.7
Vauxhall	0-15	13.0	12.8	12.5	15.0
irrigated	15-30	18.8	16.4	15.0	16.5
treatments	30-60	25.4	22.9	20.9	18.9
	60-90	12.9	12.5	13.8	14.1
	90-120	17.1	14.2	14.7	15.3

Table A5. Level of (NH_4+NO_3)-N (kg/ha) to a depth of 60 cm in unfertilized treatments over winter-spring and after harvest in September, 1977.

Plot	Fall irrigated	Sept. 1/76	Jan. 1/77	Mar. 1/77	May 1/77	Sept. 1/77	Increase from Sept. '76 to May
Vauxhall	no	28	29	44	42	28	14
dryland	yes	34	46	51	53	22	19
Vauxhall	no	64	96	125	142	37	78
irrigated	yes	83	63	82	99	36	16
Lethbridge	no	25	50	69	79	78	54
dryland	yes	21	34	51	50	35	29
Lethbridge	no	135	130	204	186	107	51
irrigated	yes	83	80	152	114	51	31
Glenwood	no	33	49	65	65	44	32
dryland	yes	42	58	61	72	36	30
Glenwood	no	22	29	30	42	28	20
irrigated	yes	21	23	31	34	29	13

Table A6. Levels of soil NH_4-N and NO_3-N (kg/ha) recovered in fall, 1976 and in spring, 1977 from unfertilized treatments at the six sites of the main field experiment.

Site	Depth (cm)	Fall irrigated	September, 1976			May 1, 1977		
			NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total
Vauxhall dryland	0-15	no	4	8	12	5	17	22
	15-30		3	2	5	4	12	16
	30-60		9	2	11	8	1	9
	60-90		8	5	13	11	2	13
	90-120		9	6	15	13	6	19
	Total		33	23	56	41	38	79
	0-15	yes	4	9	13	4	25	29
	15-30		3	2	5	2	9	11
	30-60		7	8	15	5	9	14
	60-90		9	6	15	6	9	15
	90-120		9	11	20	7	12	19
	Total		32	36	68	24	64	88
Vauxhall irrigated	0-15	no	3	12	15	4	30	34
	15-30		2	14	16	3	42	45
	30-60		5	28	33	7	55	62
	60-90		12	25	37	11	63	74
	90-120		7	41	48	16	54	70
	Total		29	120	149	41	244	285
	0-15	yes	3	17	20	5	27	32
	15-30		6	21	27	3	25	28
	30-60		7	32	39	8	30	38
	60-90		6	30	36	13	16	29
	90-120		5	37	42	15	11	26
	Total		27	137	164	44	109	153
Lethbridge dryland	0-15	no	3	1	4	6	8	14
	15-30		3	3	6	6	9	15
	30-60		8	8	16	14	35	49
	60-90		8	44	52	14	78	92
	90-120		8	66	72	15	24	39
	Total		30	122	152	45	154	199
	0-15	yes	3	1	4	5	11	16
	15-30		3	2	5	5	9	14
	30-60		6	5	11	10	9	19
	60-90		9	10	19	12	18	30
	90-120		4	38	42	14	33	47
	Total		25	56	81	46	80	126

Table A6 (continued).

Site	Depth (cm)	Fall irrigated	September, 1976			May 1, 1977		
			NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total
Lethbridge irrigated	0-15	no	5	7	12	8	24	32
	15-30		5	5	10	7	25	32
	30-60		8	104	112	5	108	123
	60-90		9	221	230	15	246	261
	90-120		10	86	96	20	76	96
	Total		37	423	460	65	479	544
	0-15	yes	6	4	10	9	9	18
	15-30		3	9	12	8	20	28
	30-60		7	51	58	14	48	62
	60-90		12	183	195	13	200	213
	90-120		13	85	98	10	152	162
	Total		41	332	373	54	429	483
Glenwood dryland	0-15	no	5	7	12	14	13	27
	15-30		4	2	6	11	7	18
	30-60		8	6	14	14	6	20
	60-90		9	6	15	11	3	14
	90-120		9	5	14	11	2	13
	Total		35	26	61	61	31	92
	0-15	yes	7	9	16	15	17	32
	15-30		5	3	8	11	7	18
	30-60		5	3	8	11	7	18
	60-90		10	1	11	13	3	16
	90-120		9	3	12	13	3	16
	Total		40	24	64	68	37	105
Glenwood irrigated	0-15	no	4	3	7	9	7	16
	15-30		4	2	6	8	2	10
	30-60		7	2	9	14	2	16
	60-90		8	0	8	15	1	16
	90-120		13	0	13	19	1	20
	Total		36	7	43	65	13	78
	0-15	yes	5	4	9	7	7	14
	15-30		4	3	7	7	2	9
	30-60		5	1	6	8	2	10
	60-90		8	2	10	9	1	10
	90-120		13	2	15	10	0	10
	Total		35	12	47	41	12	53

---

* each value is the mean of 4 replicates.

Table A.7 Yield of grain and straw, crop N uptake, and level of soil $(NH_4^+NO_3)$-N to a depth of 60 cm after harvest.

Site	Treatment	Grain yield (t/ha)	N content of grain (kg/ha)	Straw yield (t/ha)	N content straw (kg/ha)	Total crop N uptake (kg/ha)	Residual mineral N (kg/ha)
Vauxhall dryland	nil	.91 b*	18	.81	7	25 c	28 de
	U Broadcast fall	.84 b	19	.80	8	27 c	57 abc
	AN Broadcast fall	1.02 b	23	1.00	10	33 c	60 abc
	CN Broadcast fall	1.17 b	27	1.16	12	39 bc	46 bcd
	U Banded fall	1.09 b	23	1.13	11	34 c	49 bcd
	U+ATC Banded fall	.95 b	21	.94	9	30 c	69 ab
	Fall irrigated nil	2.36 a	49	1.77	12	61 ab	22 e
	Fall irrigated + CN Broadcast	2.69 a	55	2.19	16	71 a	42 cde
	U Broadcast spring	.89 b	19	.95	9	28 c	53 abc
	AN Broadcast spring	1.35 b	30	1.24	12	42 bd	77 a
	CN Broadcast spring	1.37 b	30	1.19	11	41 bc	48 bcd
Vauxhall irrigated	nil	5.59 cd	115	4.15	41	156 b	37 a
	U Broadcast fall	6.52 abc	139	4.77	48	187 ab	43 a
	AN Broadcast fall	6.30 abc	139	4.52	47	186 ab	47 a
	CN Broadcast fall	6.65 ab	142	4.70	49	191 ab	71 a
	U Banded fall	6.60 abc	145	4.85	56	201 a	42 a
	U+ATC Banded fall	6.23 abc	138	4.92	52	190 ab	63 a
	Fall irrigated nil	5.10 d	96	3.41	25	121 c	36 a
	Fall irrigated + CN Broadcast	5.85 bcd	122	4.32	45	167 ab	50 a
	U Broadcast spring	7.36 a	155	4.91	50	205 a	43 a
	AN Broadcast spring	6.26 abc	131	4.75	48	179 ab	42 a
	CN Broadcast spring	6.41 abc	138	4.66	50	188 ab	78 a

Table A7 (Continued).

Site	Treatment		Grain yield (t/ha)	N content of grain (kg/ha)	Straw yield (t/ha)	N content straw (kg/ha)	Total crop N uptake (kg/ha)	Residual mineral N (kg/ha)
Lethbridge dryland	nil		.64 c	13	.76	9	22 b	78 a
	U Broadcast	fall	.62 c	15	.96	15	30 b	87 a
	AN Broadcast	fall	.93 abc	23	1.10	14	37 ab	84 a
	CN Broadcast	fall	.83 bc	17	.99	14	31 b	59 a
	U Banded	fall	.44 c	11	1.03	18	29 b	58 a
	U+ATC Banded	fall	.56 c	13	.81	11	24 b	51 a
	Fall irrigated	nil	1.28 ab	26	1.00	8	34 ab	35 a
	Fall irrigated	+ CN Broadcast	1.48 a	32	1.36	13	45 a	62 a
	U Broadcast	spring	.74 bc	17	1.22	18	35 ab	128 a
	AN Broadcast	spring	.84 bc	20	1.09	14	34 ab	106 a
	CN Broadcast	spring	.84 bc	19	1.10	14	33 ab	77 a
Lethbridge irrigated	nil		5.02 bc	117	3.19	34	151 b	107 a
	U Broadcast	fall	5.30 abc	122	3.49	38	160 ab	83 a
	AN Broadcast	fall	5.50 abc	125	3.64	36	161 ab	62 a
	CN Broadcast	fall	5.31 abc	116	3.52	40	156 ab	110 a
	U Banded	fall	5.34 abc	125	3.50	38	163 ab	142 a
	U+ATC Banded	fall	4.88 c	113	3.37	38	151 b	96 a
	Fall irrigated	nil	5.64 ab	132	3.59	39	171 ab	51 a
	Fall irrigated	+ CN Broadcast	5.72 a	131	3.86	43	174 a	77 a
	U Broadcast	spring	5.04 abc	116	3.33	36	152 b	72 a
	AN Broadcast	spring	5.34 abc	122	3.45	35	157 ab	62 a
	CN Broadcast	spring	5.17 abc	120	3.40	35	155 ab	84 a

Table A7 (Continued).

Site	Treatment		Grain yield (t/ha)	N content of grain (kg/ha)	Straw yield (t/ha)	N content straw (kg/ha)	Total crop N uptake (kg/ha)	Residual mineral N (kg/ha)
Glenwood dryland	nil		1.39 c	26	.96	6	32 e	44 bcd
	U Broadcast	fall	1.80 c	37	1.37	13	50 bcd	68 ab
	AN Broadcast	fall	1.77 c	39	1.14	9	48 bcd	72 a
	CN Broadcast	fall	1.85 c	40	1.54	14	54 bc	76 a
	U Banded	fall	1.48 c	29	1.45	12	41 de	63 abc
	U+ATC Banded	fall	1.46 c	30	1.10	7	37 de	78 a
	Fall irrigated	nil	2.44 b	46	1.71	11	57 b	36 d
	Fall irrigated	+ CN Broadcast	3.40 a	66	2.63	16	82 a	40 cd
	U Broadcast	spring	1.46 c	30	1.40	12	42 cde	64 abc
	AN Broadcast	spring	1.86 c	39	1.23	10	49 bcd	69 a
	CN Broadcast	spring	1.66 c	35	1.12	9	44 cd	74 a
Glenwood irrigated	nil		1.02 b	16	.78	4	20 c	28 a
	U Broadcast	fall	2.24 a	31	1.76	7	38 b	24 a
	AN Broadcast	fall	2.90 a	40	2.28	11	51 a	29 a
	CN Broadcast	fall	2.22 a	32	1.94	8	40 ab	26 a
	U Banded	fall	2.40 a	33	1.91	8	41 ab	26 a
	U+ATC Banded	fall	2.56 a	35	2.12	9	44 ab	26 a
	Fall irrigated	nil	1.12 b	17	.94	5	22 c	29 a
	Fall irrigated	+ CN Broadcast	2.39 a	33	2.15	8	41 ab	24 a
	U Broadcast	spring	2.60 a	36	1.94	7	43 ab	31 a
	AN Broadcast	spring	2.80 a	39	2.20	9	48 ab	27 a
	CN Broadcast	spring	2.89 a	39	2.45	10	49 ab	30 a

* means in any column within each site are significantly different when not followed by the same letter (P=0.05).

Table A8. Percent moisture (O.D. basis) over winter 1975-76, of soils in the fall-irrigated and non-irrigated portions of each of the sites used in the main field experiment.

Site	Depth (cm)	Fall Irrigated	Approximate date *		
			January 1	March 1	May 1/77
Vauxhall dryland	0-15	yes	13.2**	14.3	12.9
	15-30		12.5	15.2	16.0
	30-60		15.0	18.4	18.7
	60-90		18.5	17.3	18.5
	90-120		18.8	18.0	16.9
	0-15	no	12.1	13.0	12.4
	15-30		11.1	10.9	12.4
	30-60		16.3	12.4	13.3
	60-90		19.4	16.1	16.1
	90-120		18.4	17.6	16.5
Vauxhall irrigated	0-15	yes	14.0	11.8	10.6
	15-30		15.6	13.2	15.0
	30-60		15.2	13.0	14.7
	60-90		11.9	13.7	13.2
	90-120		13.2	14.9	13.1
	0-15	no	8.1	9.9	10.0
	15-30		8.7	10.5	11.9
	30-60		8.0	11.1	10.4
	60-90		12.0	11.7	12.3
	90-120		15.5	15.1	14.8
Lethbridge dryland	0-15	yes	15.4	17.0	16.1
	15-30		18.0	19.3	18.3
	30-60		13.9	15.2	15.5
	60-90		10.3	11.3	12.3
	90-120		12.5	10.1	10.6
	0-15	no	10.5	13.1	15.0
	15-30		11.1	11.8	16.8
	30-60		9.8	11.7	12.5
	60-90		11.1	9.9	10.6
	90-120		11.1	11.9	10.5
Lethbridge irrigated	0-15	yes	23.4	21.0	19.3
	15-30		19.6	19.3	18.5
	30-60		19.0	18.3	19.6
	60-90		19.5	18.0	18.8
	90-120		15.7	16.8	17.4

Table A8 (continued).

Site	Depth (cm)	Fall Irrigated	Approximate date *		
			January 1	March 1	May 1/77
Lethbridge irrigated	0-15	no	17.8	19.4	18.8
	15-30		15.4	14.9	19.4
	30-60		13.4	13.7	16.8
	60-90		16.0	13.7	17.1
	90-120		17.5	15.0	16.1
Glenwood dryland	0-15	yes	28.4	33.2	28.9
	15-30		28.9	28.6	29.3
	30-60		27.3	25.3	27.5
	60-90		26.4	22.7	25.7
	90-120		22.8	21.4	23.7
	0-15	no	22.4	20.9	20.9
	15-30		21.0	21.7	20.3
	30-60		19.9	21.1	19.6
	60-90		18.2	19.3	14.2
	90-120		19.9	21.0	19.4
Glenwood irrigated	0-15	yes	19.7	21.9	19.1
	15-30		20.6	32.5	22.5
	30-60		30.5	30.9	21.7
	60-90		18.5	15.9	18.5
	90-120		20.9	18.0	20.7
	0-15	no	20.8	22.4	19.5
	15-30		24.8	28.1	21.4
	30-60		20.9	22.6	19.2
	60-90		16.5	16.8	18.0
	90-120		18.8	18.4	18.7

* Sample for moisture determinations were taken on the following dates:

Vauxhall dryland	-	January 3,	March 8,	April 29, 1977
Vauxhall irrigated	-	January 3,	March 11,	April 29
Lethbridge dryland	-	January 4,	March 9,	April 28
Lethbridge irrigated	-	December 30,	March 9,	April 28
Glenwood dryland	-	December 30,	March 10,	May 1
Glenwood irrigated	-	January 11,	March 10,	April 30

** Each value is the mean of 4 values. One core was taken from each replicate of the fall irrigated and non-irrigated portions of each plot.

Table A9. Soil temperature (°C) over winter 1976-77 in fall-irrigated and non-irrigated portions of dryland plots.

			Approximate date *		
Site	Depth (cm)	Fall Irrigated	January 1	March 1	May 1/77
Vauxhall dryland	15	yes	- 4.0	+ 0.5	+14.0
	30		- 2.0	0	+10.0
	60		- 1.0	+ 0.5	+ 9.0
	90		+ 1.0	+ 1.0	+ 8.5
	15	no	- 7.0	+ 2.0	+15.0
	30		- 5.0	+ 1.5	+11.0
	60		- 5.0	+ 2.5	+ 9.0
	90		+ 1.0	+ 3.5	+ 8.5
Lethbridge dryland	15	yes	0	+ 1.0	+11.0
	30		0	0	+10.5
	60		+ 0.5	+ 0.5	+10.0
	90		+ 1.5	+ 1.5	+ 9.0
	15	no	+ 0.5	+ 5.5	+12.5
	30		+ 1.0	+ 4.0	+11.5
	60		+ 1.0	+ 3.5	+10.0
	90		+ 1.5	+ 3.0	+ 9.0
Glenwood dryland	15	yes	- 3.5	+ 0.5	+ 8.5
	30		- 1.5	+ 0.5	+ 8.0
	60		- 0.5	+ 0.5	+ 8.0
	90		+ 2.0	+ 1.0	+ 7.0
	15	no	- 5.0	+ 1.0	+10.0
	30		- 0.5	+ 2.0	+ 9.5
	60		+ 0.5	+ 2.5	+ 9.0
	90		+ 1.0	+ 2.5	+ 8.5

* temperature readings using thermocouples at depth, insulated leads, and an electrical resistance meter were made on the following dates:

Vauxhall - December 28, 1976, March 6, and April 29, 1977
Lethbridge - December 30, 1976, March 7, and April 28, 1977
Glenwood - January 4, March 3, and May 1, 1977

Table A10. Mean monthly soil temperature (°C) at a depth of 10 cm under sod at Lethbridge CDA station, and difference from 11-year average (1967-1977).

Month/year	Temp. °C	Difference from average (C°)	Month/year	Temp. °C	Difference from average (C°)
September/75	12.5	-0.1	September/76	14.4	+1.8
October	5.9	-0.5	October	7.2	+0.8
November	0.6	-0.5	November	1.8	+0.7
December	-0.9	+1.1	December	-0.7	+1.4
January/76	-1.6	+1.9	January/77	-2.5	+1.0
February	-0.8	+1.3	February	0.5	+2.6
March	0.3	-0.2	March	1.4	+0.9
April	7.1	+2.3	April	7.4	+2.6
May	13.0	+2.0	May	12.3	+1.3
June	14.7	-1.2	June	18.3	+2.4
July	18.9	0	July	18.9	0
August	17.5	-0.6	August	16.6	-1.5

- readings taken at 8:00 a.m., daily

source - Environment Canada Meteorological data

Table A11. Monthly precipitation (mm) and mean daily temperature (°C) at Vauxhall and Lethbridge.

	Vauxhall		Lethbridge			
Month	Precip.	Temp.	Precip.	Difference from mean*	Temp.	Difference from mean
January/76			7.6	-16.5	- 4.6	+ 5.2
February			9.7	-14.0	- 2.7	+ 3.4
March			14.7	- 9.6	- 1.4	+ 1.2
April	20.1	7.2	18.8	-15.1	7.2	+ 0.9
May	21.8	13.3	42.4	-11.6	13.1	+ 2.5
June	53.3	13.6	63.0	-12.7	13.2	+ 1.5
July	34.0	18.2	41.7	0	18.1	0
August	43.7	18.3	75.4	+36.8	17.6	+ 0.7
September	10.2	14.2	14.5	-25.8	14.8	+ 2.9
October	9.9	4.5	11.7	-10.9	5.4	- 1.5
November			12.7	+ 6.1	0.7	0
December			7.9	-11.5	- 2.2	+ 3.6
January/77			32.5	+12.7	- 9.0	+ 0.1
February			0.5	-18.0	3.3	+10.0
March			27.8	+ 4.4	0.1	+ 2.3
April	1.3	8.5	8.4	-23.6	8.7	+ 3.4
May	46.2	11.8	27.2	-26.8	11.5	+ 0.9
June	26.9	17.3	29.2	-46.5	17.0	+ 2.3
July	8.1	17.6	11.7	-29.9	17.3	- 0.7
August	38.1	14.9	60.2	+21.6	14.9	- 2.0

- Environment Canada Meteorological data. Temperature of air at 120 cm above ground, recorded daily at 8:00 a.m.

* Difference from 76 year mean for temperature and precipitation. Winter data is are not recorded at Vauxhall.

Table A12. Levels of (NH_4+NO_3)-N in unfertilized soils at zero-time, and after incubation at -1° or +4°C.

Soil	Depth (cm)	ug N/g soil zero-time	-1°C	+4°C
Lethbridge dryland	0-15	19.6	9.0	11.8
	45-60	5.5	7.7	8.8
Lethbridge irrigated	0-15	22.2	25.4	31.5
	45-60	7.2	8.3	6.3
Malmo	0-15	22.6	24.5	27.1
	45-60	8.9	8.0	8.9

Table A13. Percent moisture (O.D. basis) of soils used in ^{15}N incubation experiment when collected from field, and at tensions of 31, 15, 1/3 and 0 bars.

Soil	Depth (cm)	Field moist*	Air-dry	-15 bars	-1/3 bar	0 bar
Lethbridge dryland	0-15	11.0	1.82	10.1	21.4	42.5
	45-60	7.6	1.82	9.9	22.2	43.8
Lethbridge irrigated	0-15	14.8	2.40	13.9	26.6	51.2
	45-60	11.8	2.30	12.2	23.8	47.5
Malmo	0-15	27.2	3.56	21.5	39.8	65.0
	45-60	21.8	2.94	18.7	32.4	58.7

* moisture of the soil when the samples were collected in January, 1977.

Table A14. Atom % abundance ^{15}N (%Ab), and atom % excess (%ES) ^{15}N of the N in KCL-extracted and steam-distilled samples.

Soil	Depth (cm)	N source	Incubation treatment	% Ab		Spiked (+)		% ES	
				NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Lethbridge dryland	0-15	$(^{15}NH_4)_2\ SO_4$	0 time	9.7119	.4270	-	+	9.3391	1.8094
			-1°C	9.2728	.9641	-	+	8.9000	6.4646
			+4°C	2.3449	2.3462	+	+	7.8242	6.9150
	45-60	$(^{15}NH_4)_2\ SO_4$	0 time	8.5758	.3980	-	+	8.2040	1.1459
			-1°C	10.3735	.5342	-	+	10.0017	3.0375
			+4°C	3.6748	.8730	+	+	9.4414	6.7859
	0-15	$K^{15}NO_3$	0 time	.3764	10.6112	+	-	.4724	10.2384
			-1°C	.3781	10.8116	+	-	.4358	10.4388
			+4°C	.3891	10.1322	+	-	1.2942	9.7592
	45-60	$K^{15}NO_3$	0 time	.3923	10.8069	+	-	1.5171	10.4371
			-1°C	.3986	10.0294	+	-	1.8803	10.6576
			+4°C	.3933	10.5382	+	-	1.6659	10.1664
Lethbridge irrigated	0-15	$(^{15}NH_4)_2\ SO_4$	0 time	9.4213	.6305	-	+	9.0503	1.7497
			-1°C	1.4761	7.5667	+	-	6.7107	7.1957
			+4°C	.4285	7.7365	+	-	2.4209	7.3655
	45-60	$(^{15}NH_4)_2\ SO_4$	0 time	9.2708	.4174	-	+	8.8999	3.1087
			-1°C	9.5251	.6841	-	+	9.1542	6.1101
			+4°C	2.7659	2.0120	+	+	8.4999	7.5689
	0-15	$K^{15}NO_3$	0 time	.4055	9.4157	+	-	.9949	9.0047
			-1°C	.4004	9.1288	+	-	1.1441	8.7578
			+4°C	.3842	8.6893	+	-	.8973	8.3183
	45-60	$K^{15}NO_3$	0 time	.3906	10.1046	+	-	1.0313	9.7337
			-1°C	.4018	10.6382	+	-	3.0893	10.2673
			+4°C	.3879	10.3971	+	-	.5960	10.0262

Table A14 (Continued).

Soil	Depth (cm)	N source	Incubation treatment	% Ab		Spiked (+)		% ES	
				NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Malmo	0-15	$(^{15}NH_4)_2SO_4$	0 time	3.2111	.5347	-	+	8.4669	1.1113
			-1°C	1.9662	2.2384	+	+	6.9290	6.1766
			+4°C	.5470	6.9560	+	-	2.8912	6.5855
	45-60	$(^{15}NH_4)_2SO_4$	0 time	3.0367	.4065	-	+	8.0275	.9361
			-1°C	2.6160	.6911	+	+	8.4574	5.6994
			+4°C	2.2667	1.1315	+	+	7.7242	5.9896
	0-15	$K^{15}NO_3$	0 time	.3909	9.8921	+	-	.3327	9.5216
			-1°C	.3815	9.4865	+	-	.3619	9.1160
			+4°C	.3774	8.8068	+	-	.2569	8.4363
	45-60	$K^{15}NO_3$	0 time	.3912	9.9760	+	-	.4803	9.6052
			-1°C	.3886	10.6517	+	-	1.0360	10.2809
			+4°C	.3902	10.6780	+	-	.5974	10.3072

Spike = addition of 1 mg N as NH_4Cl solution

Table A15. Atom % abundance ^{15}N (%Ab), and atom % excess ^{15}N (%ES) of the N in Kjeldahl-digested samples, modified to include NO_3 and NO_2-N.

Soil	Depth (cm)	N source	Incubation treatment	% Ab	% ES
Lethbridge dryland	0-15	$(^{15}NH_4)_2\ SO_4$	0 time	.9536	.5808
			-1°C	.9765	.6037
			+4°C	.9403	.5675
	45-60	$(^{15}NH_4)_2\ SO_4$	0 time	1.0710	.6992
			-1°C	1.0671	.6953
			+4°C	nd	
	0-15	$K^{15}NO_3$	0 time	.8915	.5187
			-1°C	1.1103	.7385
			+4°C	nd	
	45-60	$K^{15}NO_3$	0 time	1.0569	.6851
			-1°C	1.1564	.7846
			+4°C	nd	
Lethbridge irrigated	0-15	$(^{15}NH_4)_2\ SO_4$	0 time	.7907	.4197
			-1°C	.7874	.4164
			+4°C	nd	
	45-60		0 time	nd	
			-1°C	1.3668	.9959
			+4°C	1.1898	.8189
	0-15	$K^{15}NO_3$	0 time	.7112	.3402
			-1°C	1.1555	.7846
			+4°C	.7781	.3710
	45-60	$K^{15}NO_3$	0 time	nd	
			-1°C	1.1730	.7021
			+4°C	1.2913	.9204

Table A15 (continued).

Soil	Depth (cm)	N source	Incubation treatment	% Ab	% ES
Malmo	0-15	$(^{15}NH_4)_2\ SO_4$	0 time	nd	
			-1°C	.5423	.1718
			+4°C	.5612	.37
	45-60	$(^{15}NH_4)_2\ SO_4$	0 time	.6949	.3241
			-1°C	.7066	.3358
			+4°C	nd	
	0-15	$K^{15}NO_3$	0 time	.4144	.0439
			-1°C	.5510	.1805
			+4°C	.5612	.1907
	45-60	$K^{15}NO_3$	0 time	.7010	.3302
			-1°C	.6967	.3259
			+4°C	.6989	.3281

* not done due to broken shell vials or to faulty readings.

Table A16. Natural atom % abundance ^{15}N of soils used in N-15 incubation experiment.*

Soil	Depth (cm)	Natural abundance (ANS)
Lethbridge	0-15	.3728
dryland	45-60	.3718
Lethbridge	0-15	.3710
irrigated	45-60	.3709
Malmo	0-15	.3705
	45-60	.3708

* abundance calculated from samples prepared from unlabelled, total N distillations.